دانشگاه سمنان

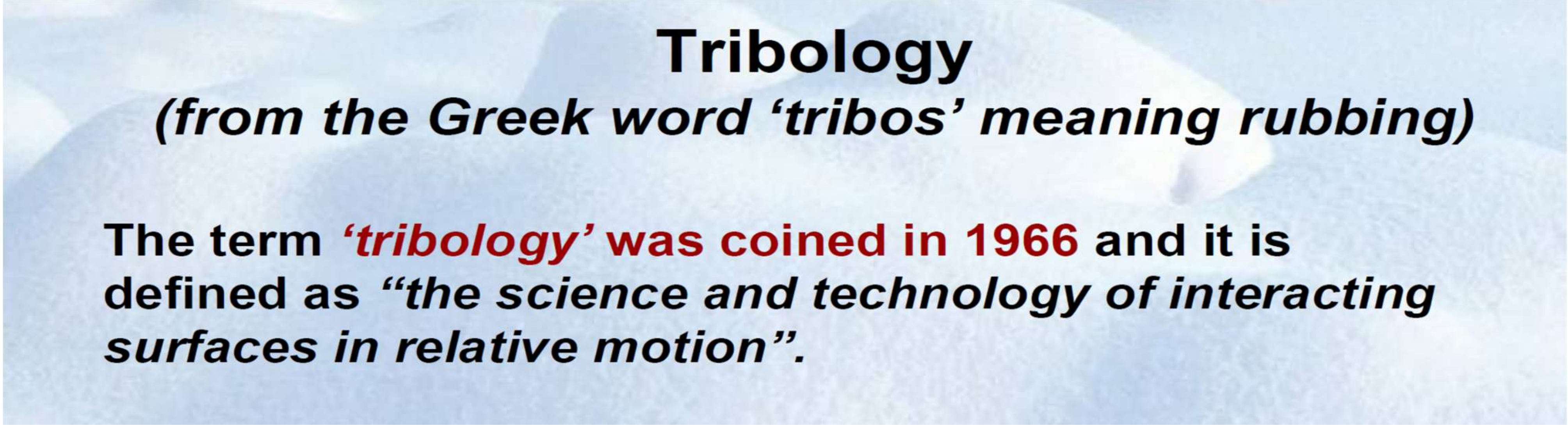
Tribology

Collected by: M. Azadi

References

- Friction, wear, lubrication, A textbook in tribology, K.C Ludema, 1996 CRC Press.
- The Tribology Handbook, 1989, published by Halstead Press (Ed. M.J. Neale).
- The ASM (Vol. 18) Handbook of Tribology, 1994 (Ed. P.J. Blau)

Introduction



Tribology

(from the Greek word 'tribos' meaning rubbing)

The term ***'tribology'* was coined in 1966** and it is defined as *"the science and technology of interacting surfaces in relative motion"*.

Science: Basic mechanisms

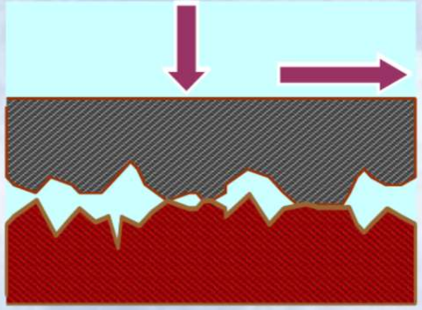
Technology: Design, manufacture, maintenance

It encompasses the study of:

Friction

Wear

Lubrication



Tribology

Friction is defined as the resistance to motion experienced whenever one solid body moves over another.

Friction

Resistance to relative motion

Wear is defined as surface damage or removal of material from one or both solid surfaces during moving contact.

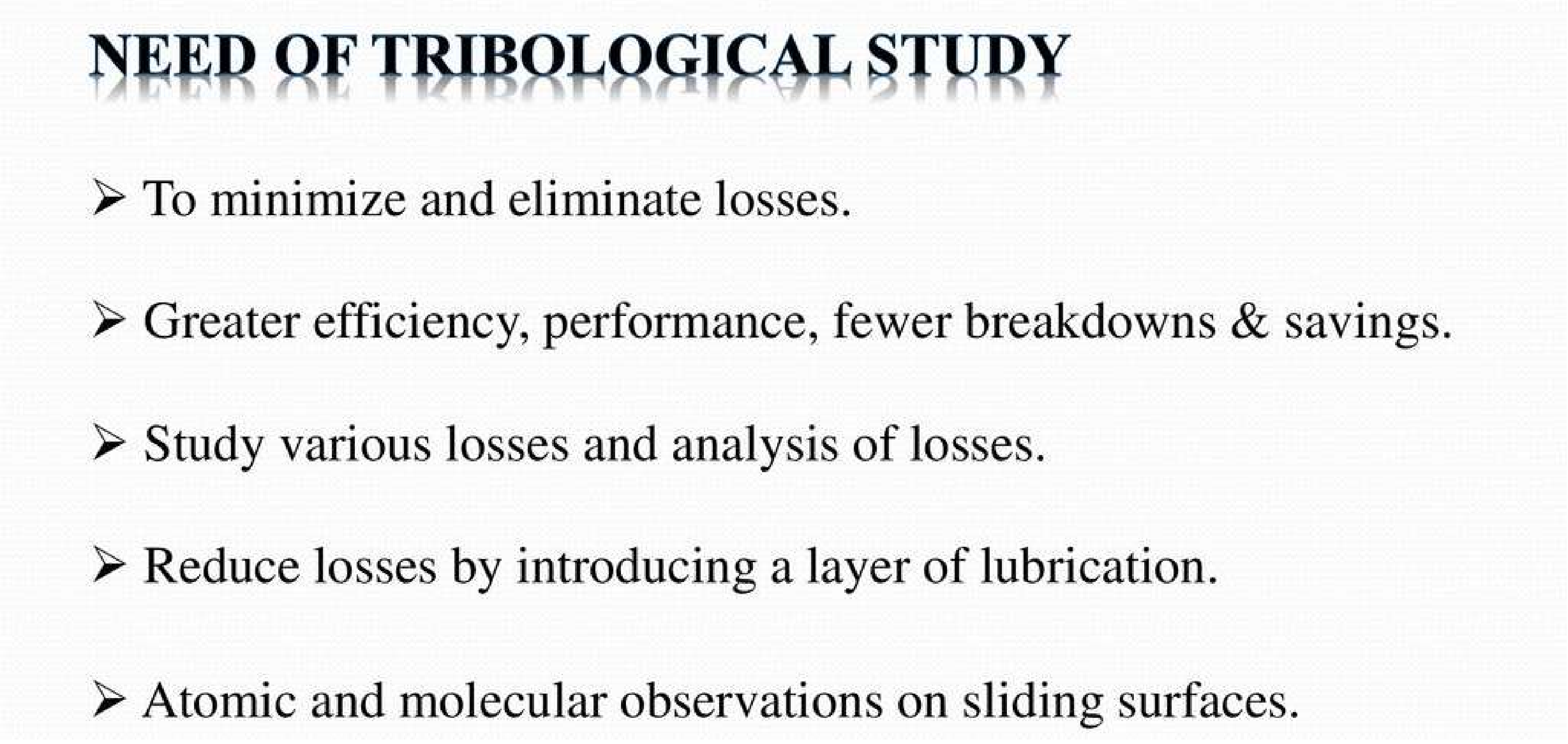
Wear

Gradual removal, damaging or displacement of material.

One of the most effective means of controlling friction and wear is by proper lubrication, which provides smooth running and satisfactory life for machine elements. Lubricants can be solid or gaseous.

Lubrication

Control of friction and wear by introducing a friction-reducing film between moving surfaces in contact.



NEED OF TRIBOLOGICAL STUDY

- To minimize and eliminate losses.
- Greater efficiency, performance, fewer breakdowns & savings.
- Study various losses and analysis of losses.
- Reduce losses by introducing a layer of lubrication.
- Atomic and molecular observations on sliding surfaces.

Probably more failures are caused by tribological problems than fracture, fatigue, plastic deformation.

The Importance of Tribology

Energy Efficiency

Optimizing tribological systems can lead to significant energy savings by reducing friction and wear.

Cost Reduction

Improved tribological design can extend extend the lifespan of components and and machinery, lowering maintenance maintenance and replacement costs. costs.

Sustainability

Tribology plays a crucial role in enabling enabling more sustainable engineering engineering practices by improving resource efficiency.

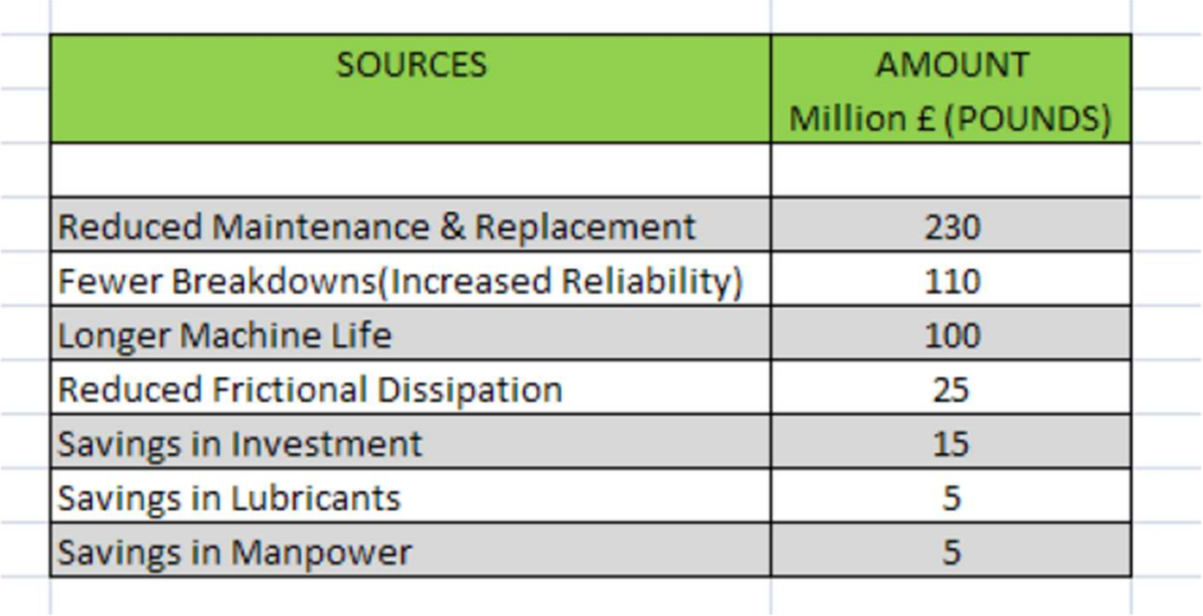
Safety and Reliability

Understanding and controlling tribological phenomena is essential for for ensuring the safe and reliable operation of mechanical systems.

Tribological knowledge helps to improve service life, safety, and reliability of interacting machine components; and yields substantial economic benefits.

Most tribological phenomena are inherently *complicated and interconnected*, making it necessary to understand the concepts of tribology in detail.

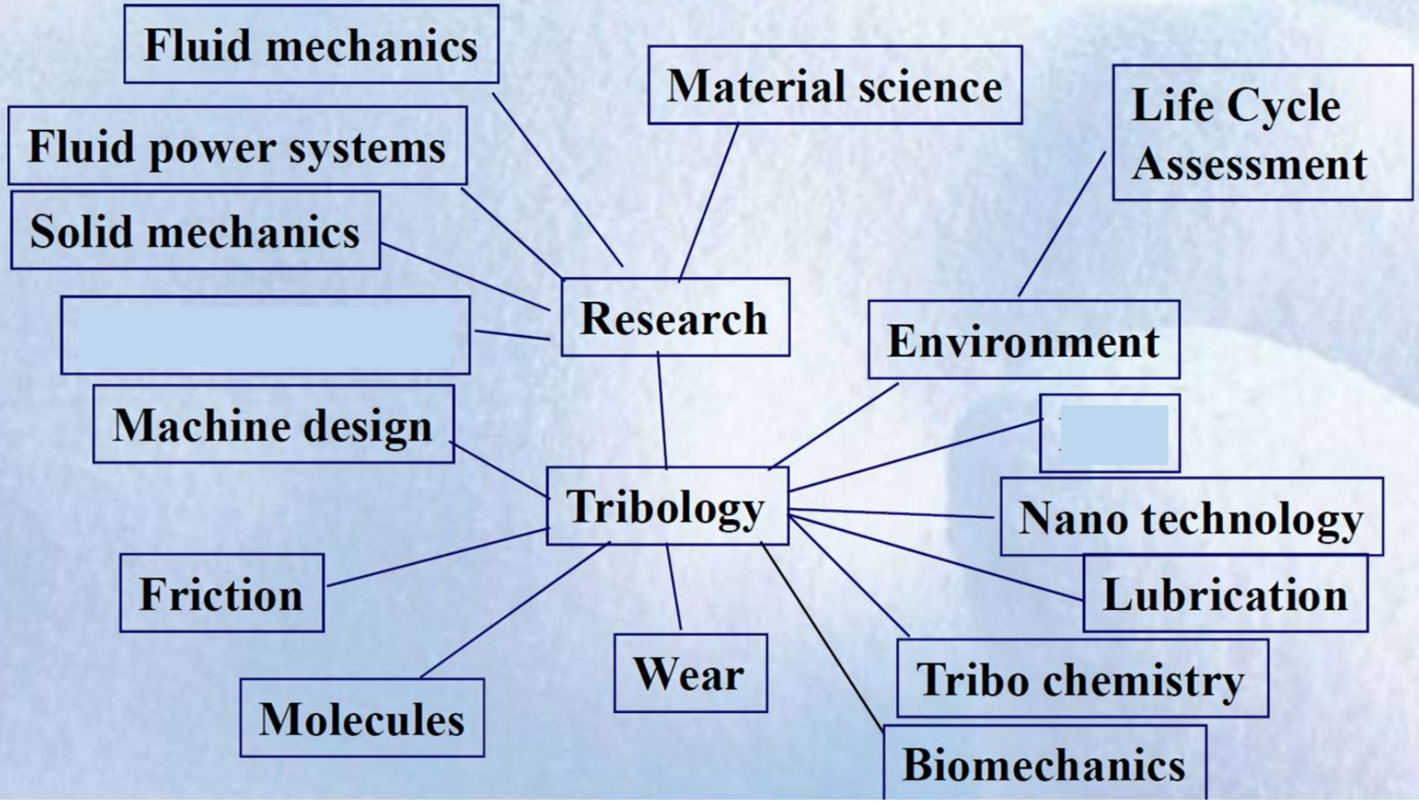
Integration of knowledge from multi-disciplines (solid mechanics, fluid mechanics, material science, chemistry etc) is essential and therefore a separate subject is required.

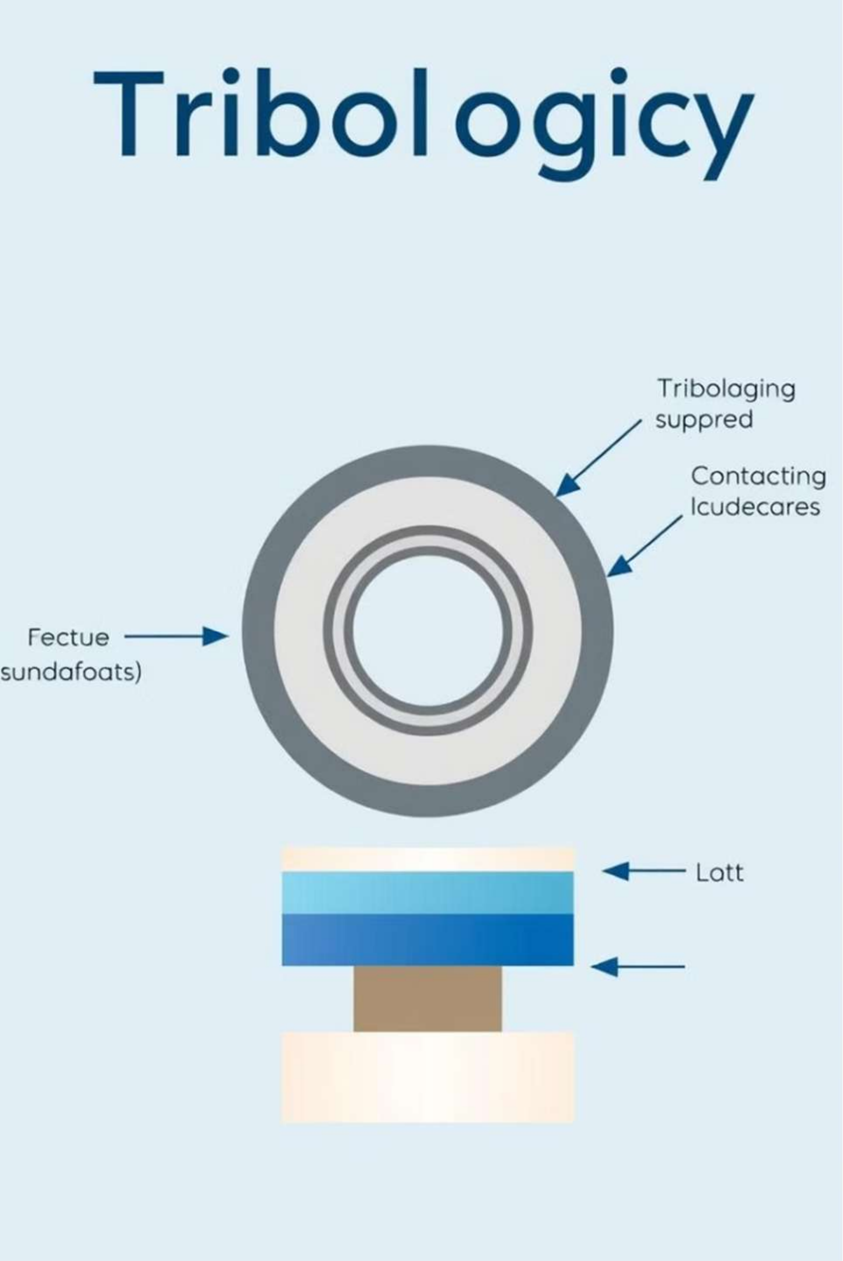


SOURCES	AMOUNT Million £ (POUNDS)
Reduced Maintenance & Replacement	230
Fewer Breakdowns(Increased Reliability)	110
Longer Machine Life	100
Reduced Frictional Dissipation	25
Savings in Investment	15
Savings in Lubricants	5
Savings in Manpower	5

SAVINGS RELSULTING FROM PROPER UNDERSTANDING AND APPLICATION OF TRIBOLOGY

Tribology is a Multi-Disciplinary Subject





Definition and Scope of Tribology Tribology

1 Multidisciplinary Field

Tribology draws on principles from physics, chemistry, materials materials science, and engineering to understand and and optimize surface interactions. interactions.

2 Wide-Ranging Applications

Tribology impacts a diverse range of industries, from transportation and machinery to biomedical devices and energy systems.

3 Economic Importance

Effective tribological design can lead to significant cost savings by reducing reducing energy consumption and machine wear and tear.

Examples

Most mechanical components have one or more moving parts. This means that something is moving relative to something else, so there is tribology happening.

In some components, such as bearings and gears, the goal is to **minimize** the resistance to sliding or rolling so that as little energy as possible is lost to friction.

In other components, such as brakes and clutches, we want **maximum** sliding resistance in order to limit the relative motions.

- BEARINGS –
  Minimal friction & Minimal wear
- BRAKES –
  Maximum friction & Minimal wear
- MACHINING –
  Minimal friction & Maximum wear

Tribology is Everywere- Few Examples

- Tyre-road (high friction required)
- Bearings (low friction and wear required)
- Screw joints (low friction in threading, no wear in contact)
- Ski-snow (low friction for gliding but high in the grip zone)
- Shoe-floor (medium friction for easy walking and dancing)
- Brake-disc (controlled, stable friction, not too low or too high)
- Cam-follower (no wear, low friction)
- Piston ring-cylinder (no wear, low friction)
- Chalk-board (controlled wear process)
- Pen-paper (controlled wear process)
- Artificial joints

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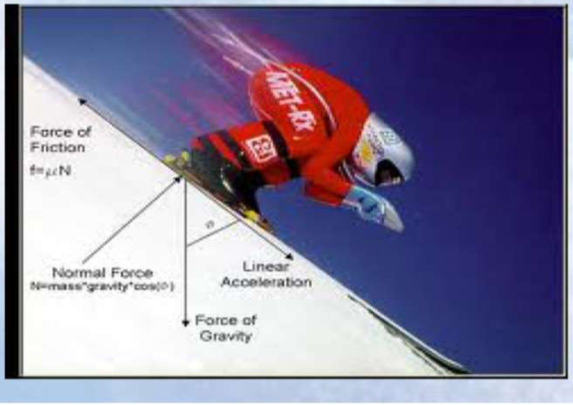

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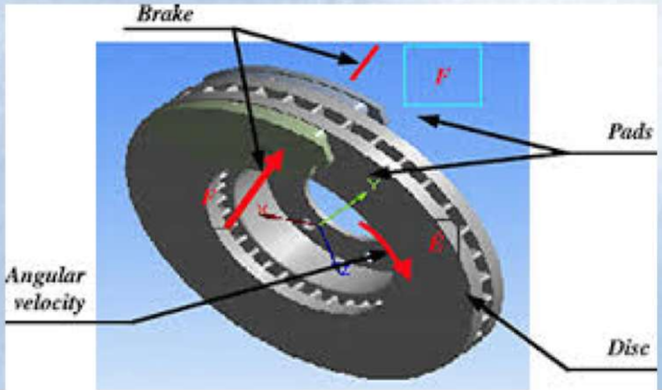

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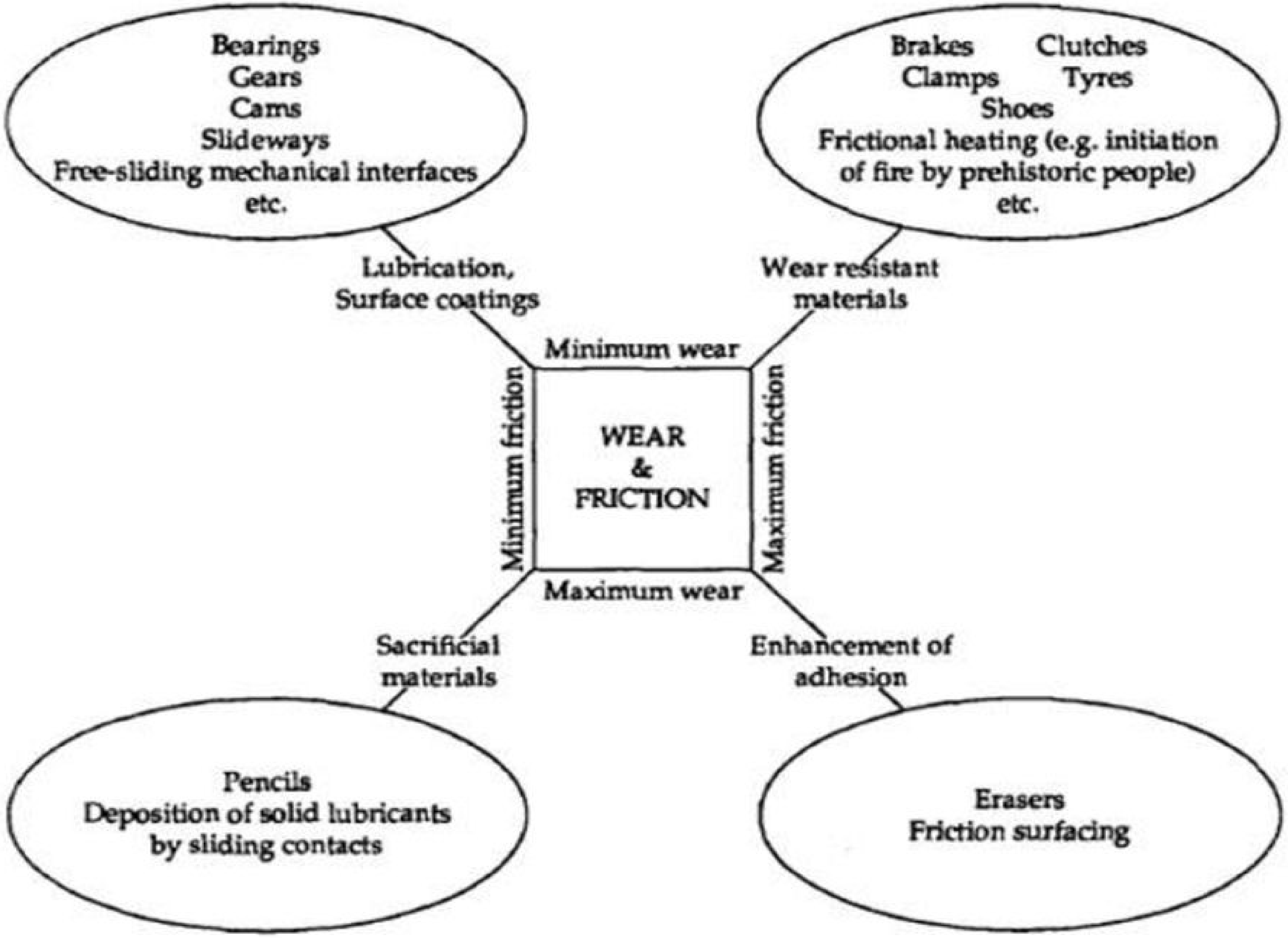


Figure Practical objectives of tribology.

Tribological Examples

- Left hand side is photograph of centrally grooved engine *journal bearing.*
- It appears that bearing is worn out due to foreign particles.

- Right hand side is a photograph of an *aluminum bearing* subjected to heavy load,
- Which causes shaft surface to run over bearing inner surface.

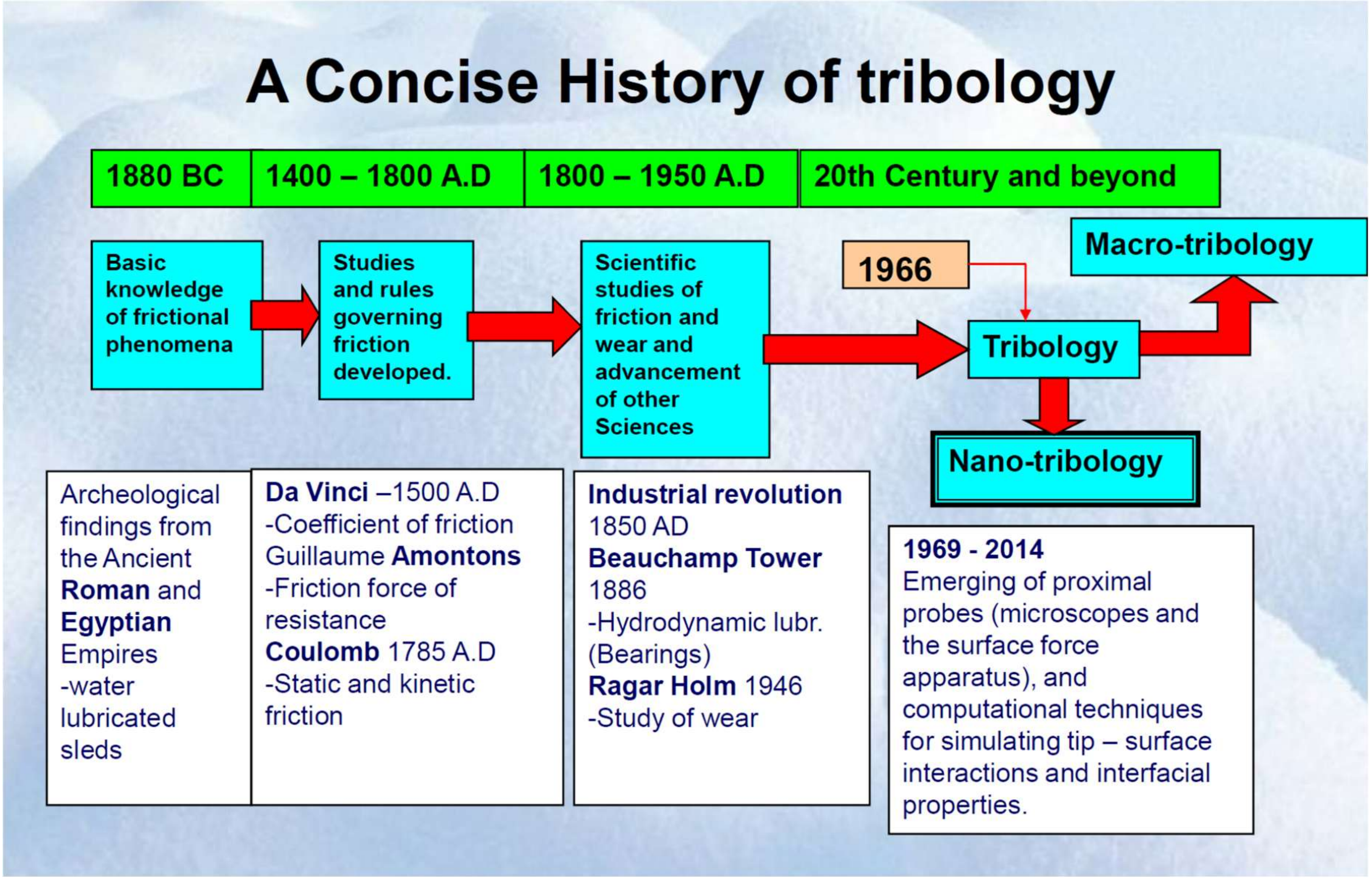
Tribological Examples

- Deep cracks which breaks outer ring in number of pieces. Such failure occurs due to faulty manufacturing and wrong assembly of *roller bearing*.
- Tribological relations help estimating increase in contact stresses due to misalignment of shaft and improper mounting of bearing surfaces.
- Hence an approximate reduction in service life can be estimated.

Tribological Examples

- A pit on the surface of *gear tooth* is shown in Fig. The pit generally occurs due to excessive contact stress.
- Understanding the effect of contact stress helps in developing an equation for estimation of perspective gear life.

History



A Concise History of tribology

1880 BC	1400 – 1800 A.D	1800 – 1950 A.D	20th Century and beyond

Basic knowledge of frictional phenomena

Studies and rules governing friction developed.

Scientific studies of friction and wear and advancement of other Sciences

1966

Tribology

Macro-tribology

Nano-tribology

Archeological findings from the Ancient **Roman** and **Egyptian** Empires
-water lubricated sleds

Da Vinci –1500 A.D
-Coefficient of friction
Guillaume **Amontons**
-Friction force of resistance
Coulomb 1785 A.D
-Static and kinetic friction

Industrial revolution
1850 AD
Beauchamp Tower
1886
-Hydrodynamic lubr. (Bearings)
Ragar Holm 1946
-Study of wear

1969 - 2014
Emerging of proximal probes (microscopes and the surface force apparatus), and computational techniques for simulating tip – surface interactions and interfacial properties.

In ancient times, on the order of about 500,000 B.C., early humans learned that by rubbing sticks together with great force they could create fire.

Around 3500 B.C. we learned that rolling motion required less effort than sliding, and the wheel was invented.

1495-1950: Laws of friction are developed

- In 1495 **Leonardo** formulated the two basic laws of friction: Friction is independent of contact area, and friction is proportional to load. For years, he never got credit for his work, as he did not formally publish his observations.

- Some 200 years later, in 1699, **Guillaume Amontons** (1663-1705) rediscovered these two basic laws. He reasoned that friction was primarily the result of work done to lift one surface over the roughness of the other, resulting in deformation and wear of the surfaces.

- **Sir Isaac Newton** (1642-1727), in studying and creating the basic laws of motion, added that moving friction was not dependent on speed or velocity, thus formulating the third law of friction. All these observations were made in the macro scale.

- In 1950, **Phillip Bowden** and **David Tabor** gave a physical explanation for the observed laws of friction. They determined that the true area of contact, which is formed by the asperities on the surface of a material, is a very small percentage of the apparent area. As the normal force increases, more asperities come into contact and the average area of each asperity contact grows.

- As our ability to analyze surface contacts at the monomolecular level has developed, we are learning that the “macro” laws don’t necessarily hold and that the processes of interaction are quite complex.

- “*Amontons Laws of Friction are the first quantitative description of a tribological process. Attempts (theories, mechanisms, models) to explain these laws have been central to the development of tribology.*” —**Bill Needelman**, Filtration Science Solutions.

1883-1905: Principles of hydrodynamic lubrication are elaborated

- In 1883, the elucidation of hydro-dynamic lubrication began in England, with testing done by **Beauchamp Tower**. He used a specially constructed test rig for journal bearings, simulating the conditions found in railway axle boxes.

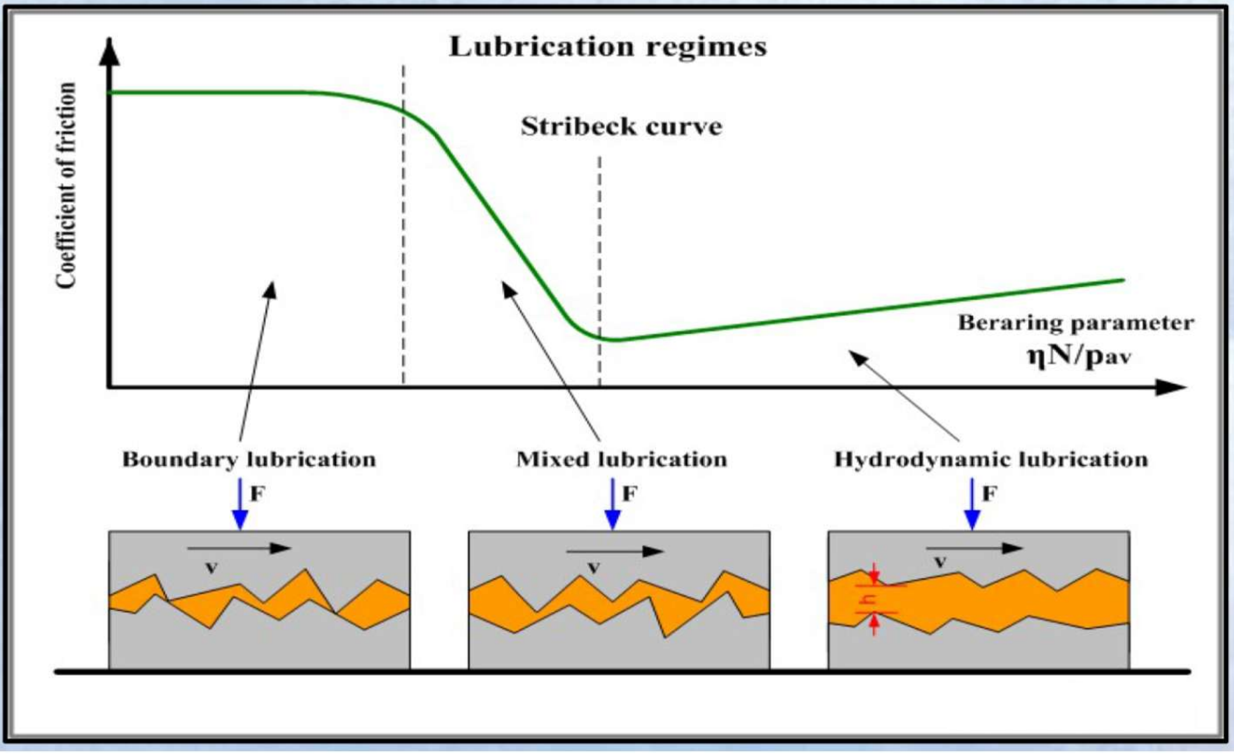
- In the final phase of his research, Tower decided to drill an oil feed hole in the bearing. The oil was found to rise upwards in the feed hole and leak over the top of the bearing cap. He then installed a pressure gauge and found it to be inadequate for measuring the high pressure levels. This result proved the existence of a fluid film that could carry significant loads.

- In 1886 **Osborne Reynolds** published a differential equation describing this pressure buildup of the oil in the narrow converging gap between journal bearing surfaces. This equation, a variation of the Navier-Stokes equations resulting in a second-order differential equation, was so complex that many years passed before it was solved for journal bearings.

- In 1902 **Richard Stribeck**, published the Stribeck curve, a plot of friction as it relates to viscosity, speed and load.

- After the work of Tower and Reynolds, **Arnold Sommerfeld** refined the work into a formal theory of hydrodynamic lubrication in about 1905.

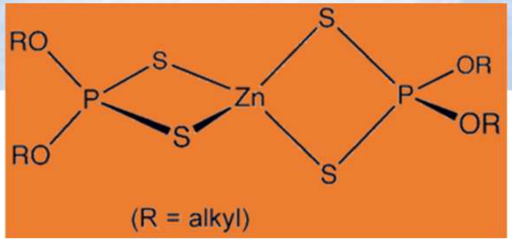
- A surface have tiny asperities that will contact if two plates are placed together. If one of the plates were to slide over the other, then friction would increase, the asperities would break and the surfaces would wear. In hydrodynamic lubrication, a fluid film separates the surfaces, prevents wear and reduces friction.



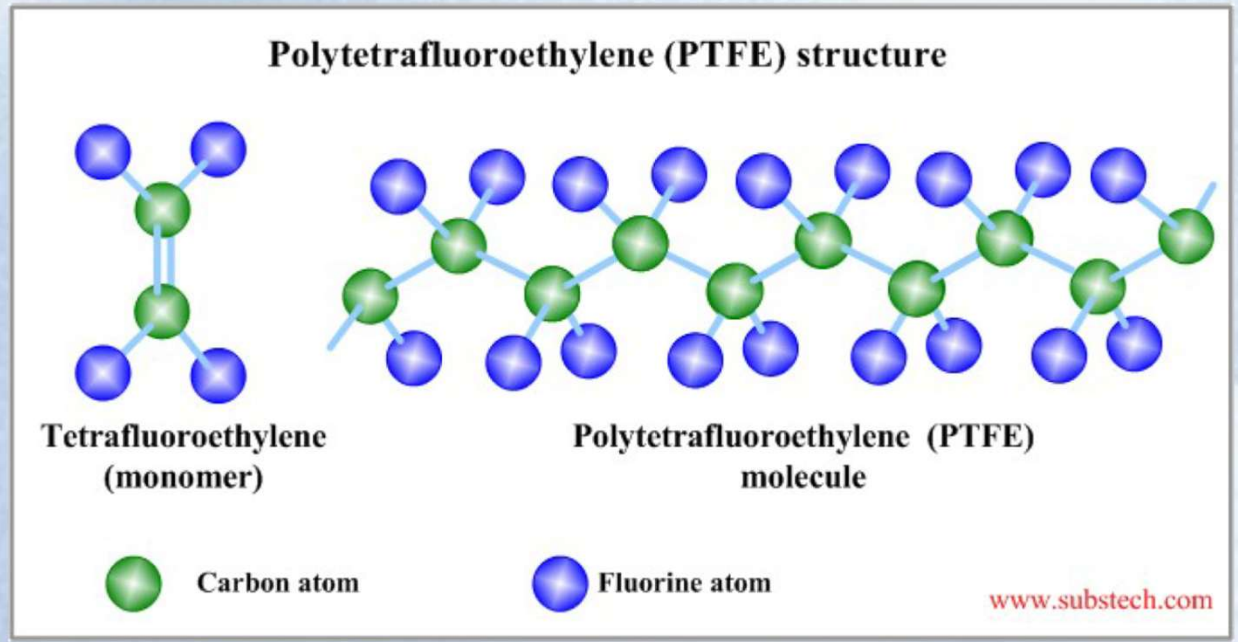
•In 1912 Dr. Albert Kingsbury invented the **hydrodynamic thrust bearing**.

•In 1922 understanding of **Boundary lubrication refined** by W.B. Hardy and I. Doubleday.

•1930s to 1940s The first **zinc dialkyldithiophosphates (ZDDPs)** began to be developed as anticorrosion agents and oxidation inhibitors. The antiwear activity of these molecules was recognized only later, in the 950s, at which point they became an integral part of many oil chemistries. To this day ZDDPs remain the backbone of antiwear additive technology.



- **PTFE**, the most famous of the self-lubricating coating materials, was discovered fortuitously during a project looking at tetrafluoroethylene as a refrigerant.



- In 1942 **Lithium grease** invented & rapidly became widely used multi-purpose grease

•In 1950 **Synthetic oils** introduced for usage in aviation.

•In 1950s **Fire Resistant Hydraulic Fluids** developed.

•In 1962 **Aluminium Complex grease** invented for high temperature applications.

•In 1960s **Multi-grade motor oils** introduced.

•In 1960s **Synthetic oils** used for motor oils.

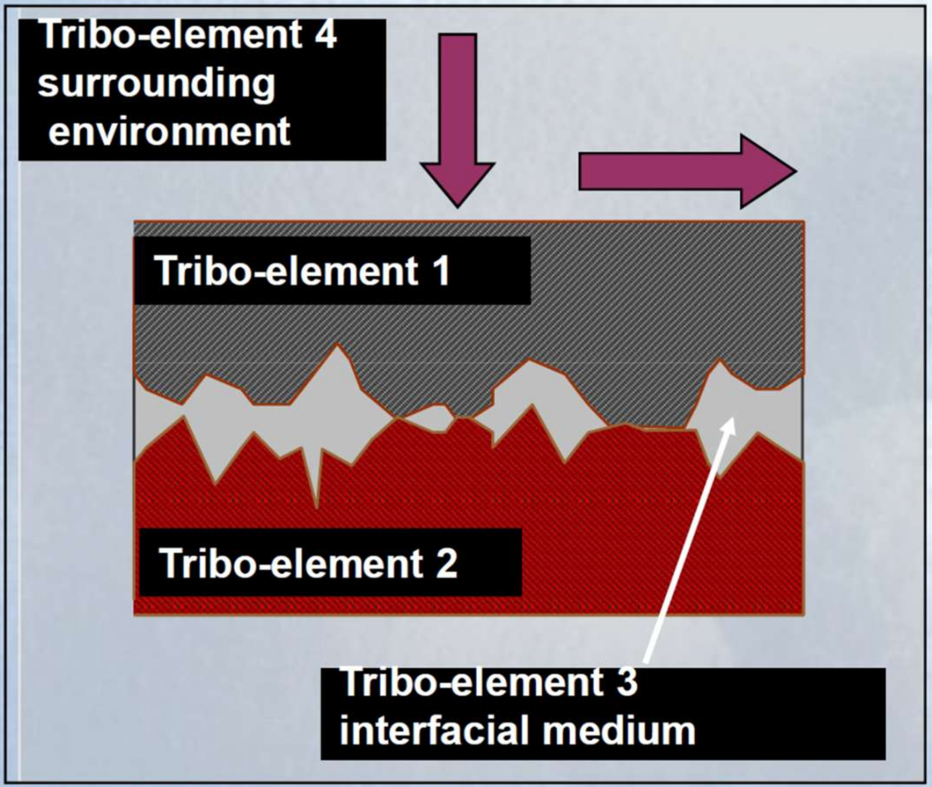
•In 1986 the development of the **Atomic Force Microscope** enabled scientists to study & understand friction at the atomic scale.

•1980 onwards **Biolubricants** developments begin.

•1990 onwards **Nanotribolgy, Biotribology** developments begin.

Basic

Tribo-system



Tribo-element 4
surrounding environment

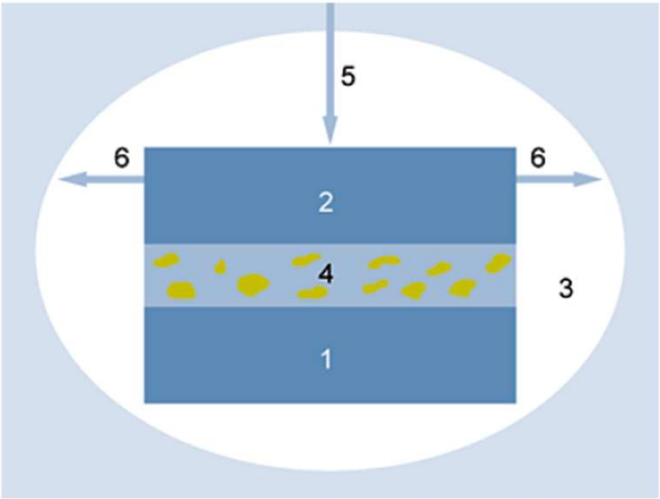
Tribo-element 1

Tribo-element 2

Tribo-element 3
interfacial medium

Tribological System

- A tribological system consists of the surfaces of two components that are in moving contact with one another and their surroundings. The type, progress and extent of wear are determined by the materials and finishes of the components, any intermediate materials, surrounding influences and operating conditions



1 Base object
2 Opponent body
3 Surrounding influences: Temperature, relative humidity, pressure
4 Intermediate material: Oil, grease, water, Particles, contaminants
5 Load
6 Motion

Surface Interactions and Contact Mechanics

Surface Topography

The roughness and texture of surfaces at the at the micro- and nano-scales significantly significantly impact tribological behavior. behavior.

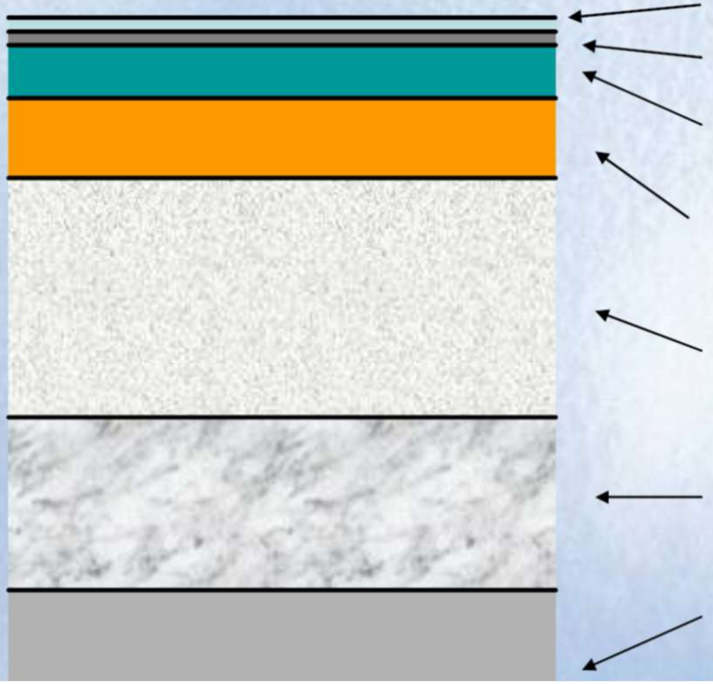
Contact Mechanics

The study of how surfaces deform and interact under load, which is crucial for understanding friction and wear phenomena. phenomena.

Surface Modification

Techniques like coatings, texturing, and surface treatments can be used to engineer engineer desirable tribological properties. properties.

The Nature of Solid Surfaces



Physisorbed layer (0.3-3 nm)

Chemisorbed layer (0.3 nm)

Chemically reacted layer (10-100 nm)

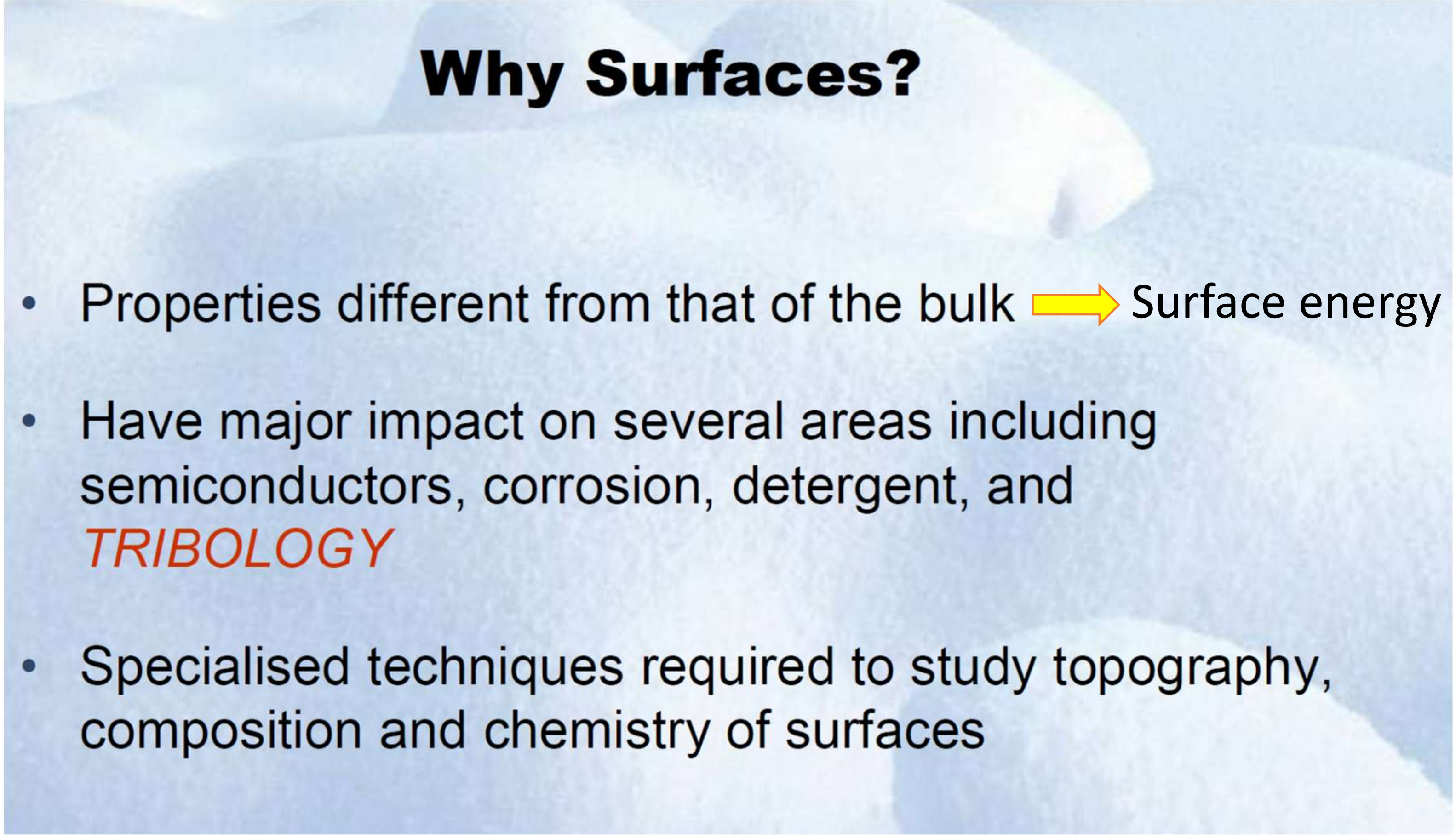
Beilby layer (1-100 nm)
(melted during machining)

Heavily deformed layer (1-10 μm)

Lightly deformed layer (1-10 μm)

Base material

Surface and roughness

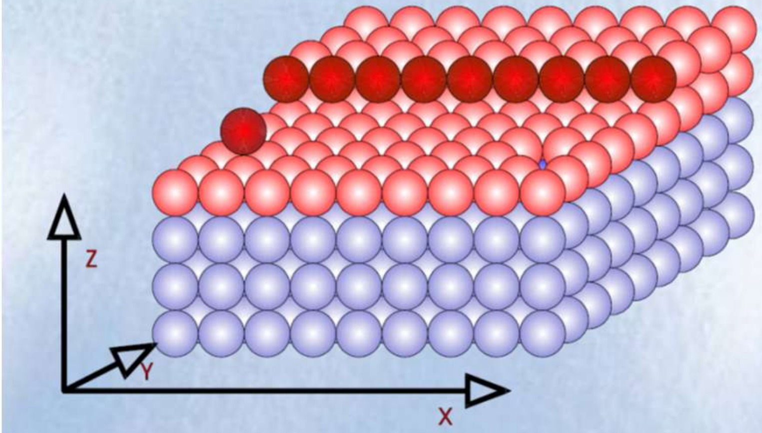


Why Surfaces?

- Properties different from that of the bulk → Surface energy
- Have major impact on several areas including semiconductors, corrosion, detergent, and *TRIBOLOGY*
- Specialised techniques required to study topography, composition and chemistry of surfaces

Surfaces

A surface is made by a sudden termination of the bulk structure. The bonding that was involved in the bulk lattice (for a solid) or liquid is severed to produce the interface.



Since it requires energy to terminate the bonding, the surface is **energetically** less stable than the bulk.

This energy is known as the **surface free energy**. In the case of liquid interfaces, this energy is called **surface tension**.

The force of static friction between two sliding surfaces is strongly dependent upon the real area of contact. Figure 6 below is a very crude representation of the profile between mating surfaces:

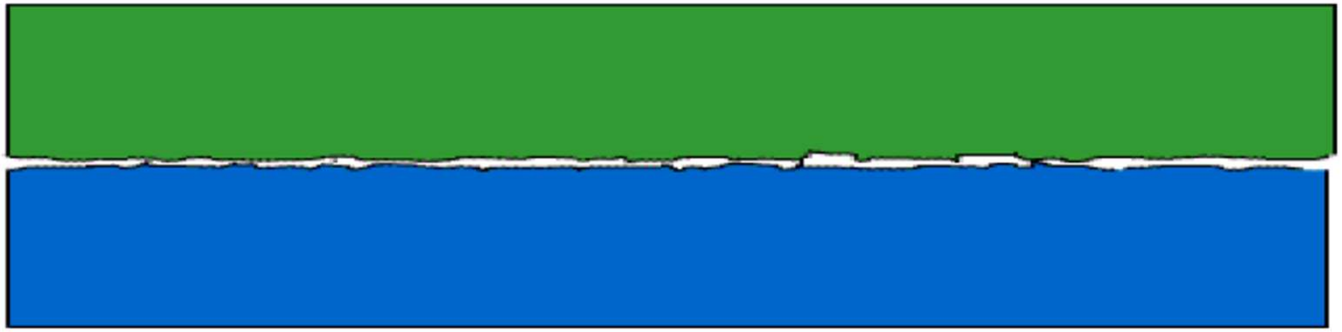
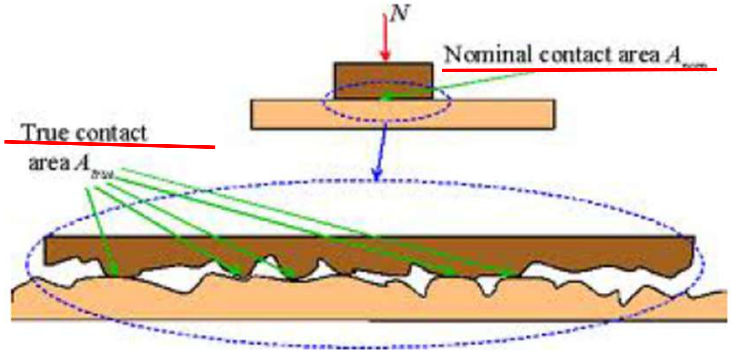


FIGURE 6: ASPERITIES OF MATING MACHINES SURFACES

Another representation



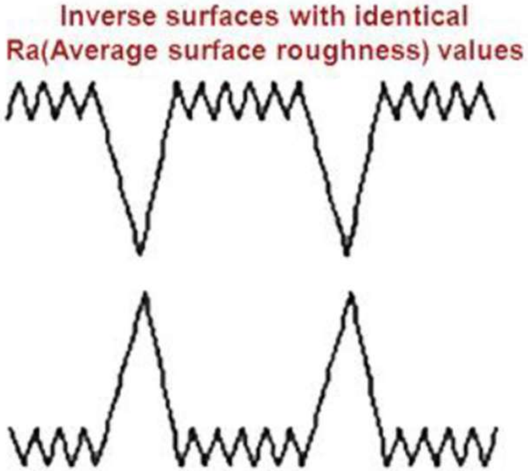
Surface Phenomenon

- In tribology, motion under load induces stresses, which leads; elastic bending, breakage or ploughing of soft surface by asperities. It appears that *surface roughness* plays an important role in tribological phenomena.

$$\sigma = \frac{F}{A}$$

- *Failure rate* of any tribo pair (two machine components in relative sliding motion) depends on the surface roughness of machine components

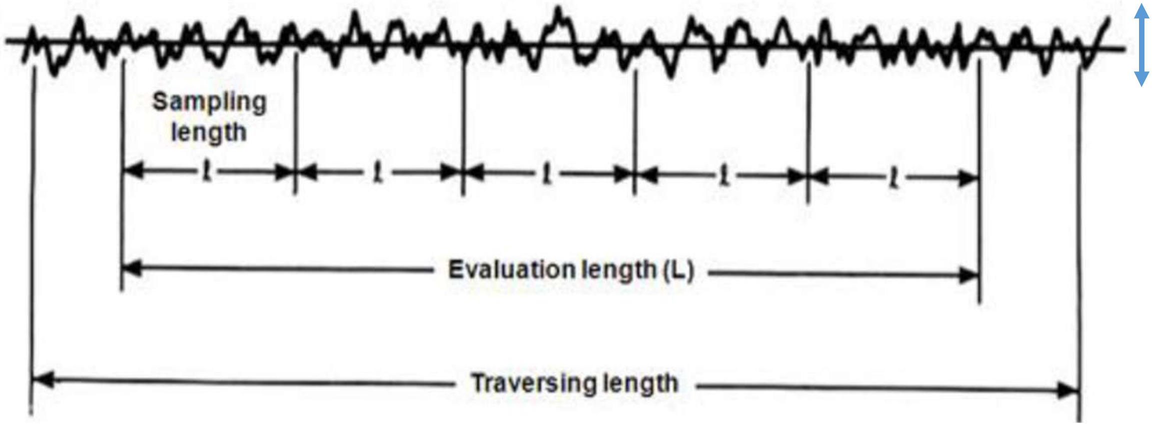
- Due to positive deviations (roughness above the nominal surface), the contact between solids confines to a very small fraction of nominally area (δA), and as a result estimated contact stress on rough surface = $F/\delta A$ are much higher in magnitude compared to nominal stresses as expressed by following equation : Stress on smooth surface = F/A



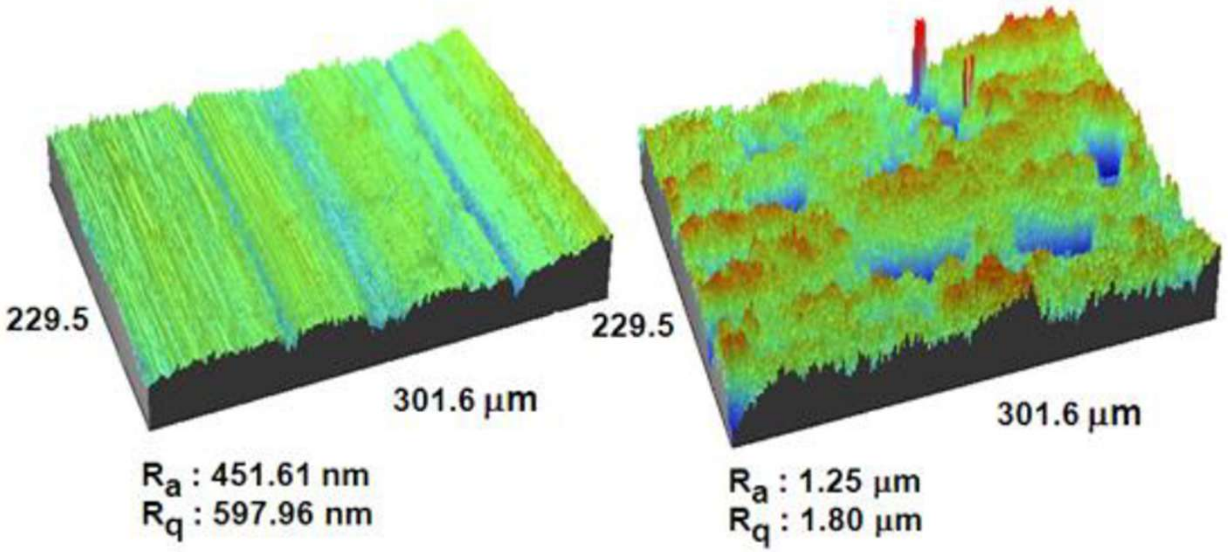
- Surface roughness is defined by short wavelength vertical deviations from nominal surface. Larger the deviations, rougher the surface. Fig. shows three different length: *Sampling length, evaluation length and traversing length*.

- This figure shows that traversing length is greater than evaluation length. This means we collect more sampling data and reject few data collected at the start and end of stylus. Further, to find statistically reliable surface roughness, averaging of roughness data over five sampling lengths is performed. Often roughness is quantified as average (R_a) and root mean square (R_q) roughness.

quadratic roughness

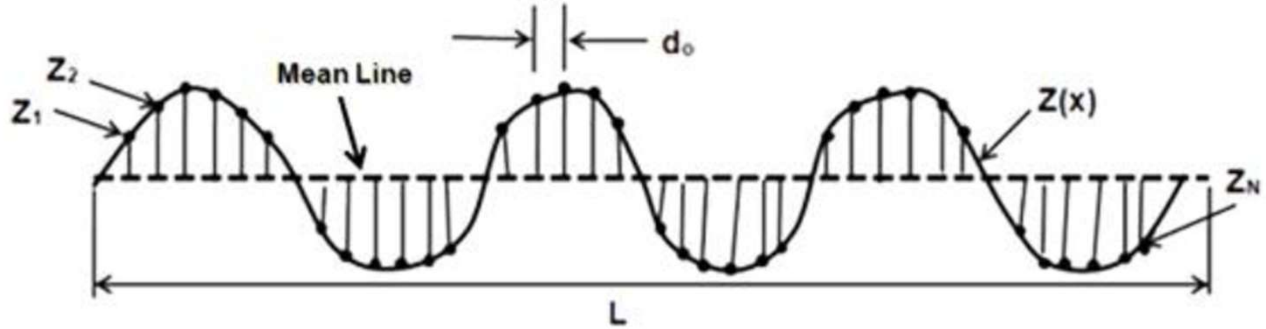


- Fig. shows too tribo-surfaces. If we compare R_a and R_q values of two images as shown in (a) and (b) respectively, we find *better performance* of (a) compared (b).
- In other words rough surfaces usually wear *more quickly* and have *higher friction coefficients* than smoother surface.



(a) Good Surface **(b) Bad Surface**

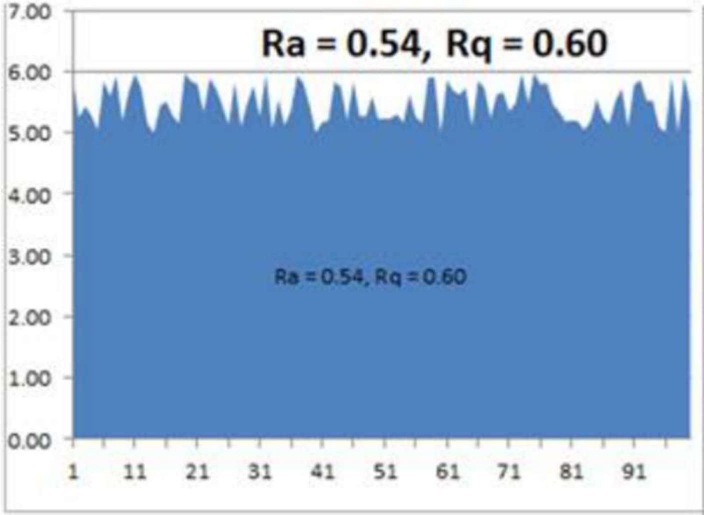
- Surface roughness is quantified by R_a and R_q values which can be calculated by *discrediting surfaces* as shown in Fig. in number of points.



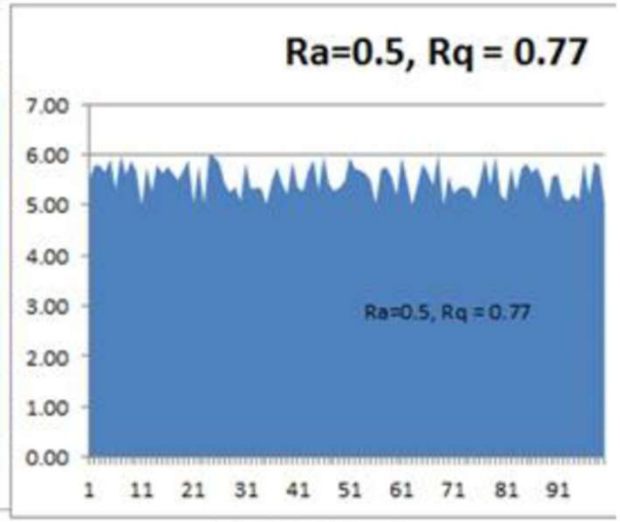
$$R_a = \left(|z_1| + |z_2| + \ldots |z_{N-1}| + |z_N|\right) / N$$

$$R_q = \sqrt{\left(\frac{z_1^2 + z_2^2 + \ldots z_{N-1}^2 + z_N^2}{N}\right)}$$

- From Tribology point of view R_q(root mean square) roughness is *preferred* over R_a(Average) roughness. Fig. (a) surface is treated as a good surface compared to surface shown in Fig. (b) due to lower value of R_q .
- This feature is often missed on comparing R_a value of two surfaces that is why comparing R_q values is *more important* than R_a values.



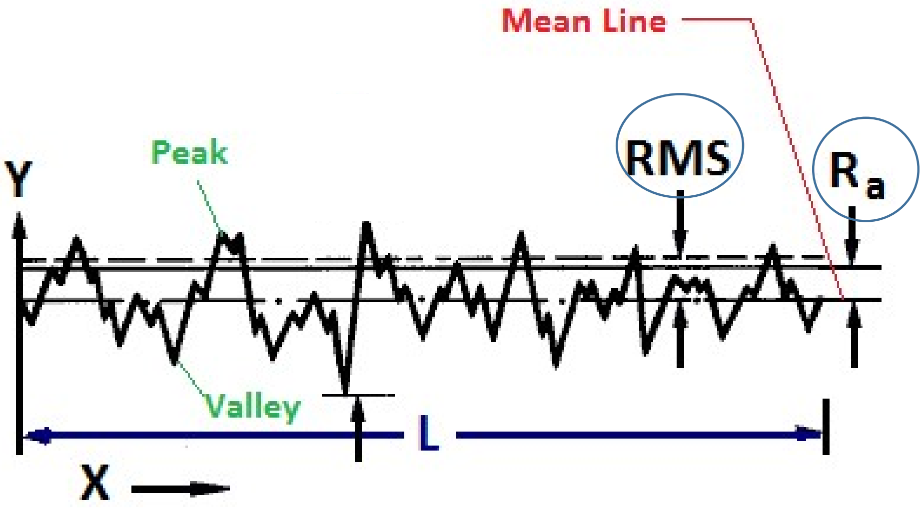
(a) Good Surface



(b) Bad Surface

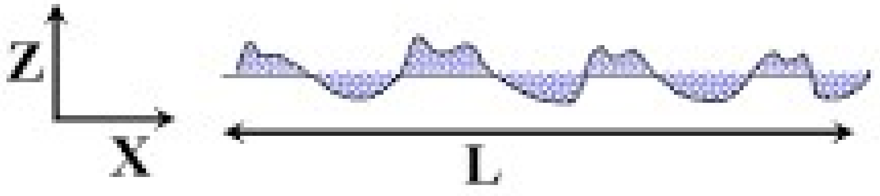
Numerical

- Take actual reading and calculate RA and RMS value of three different kind of surface of actual machine components.

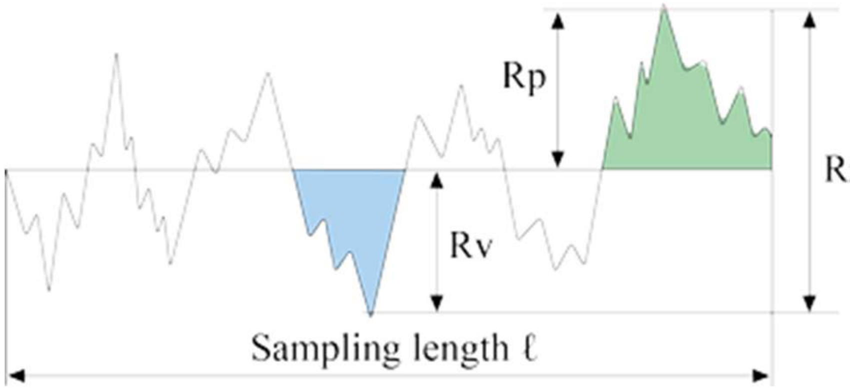


Ra (average roughness) measures the deviation of a surface from a mean height. The horizontal line through the profile represents the arithmetic mean height. The blue areas represent the deviations from that line.

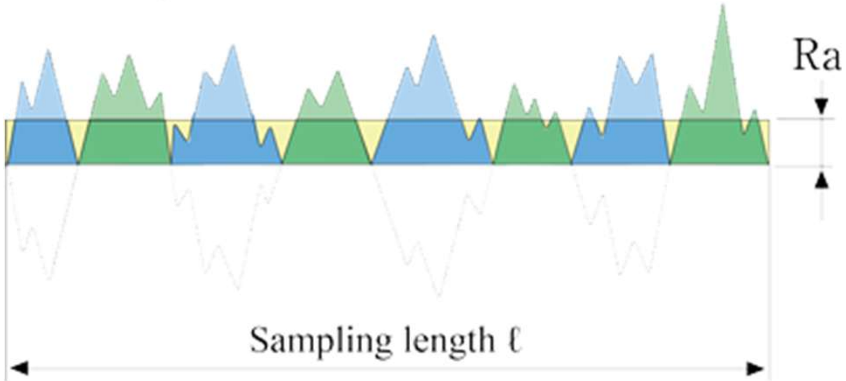
Ra, then, is the total blue area divided by the length of the profile.



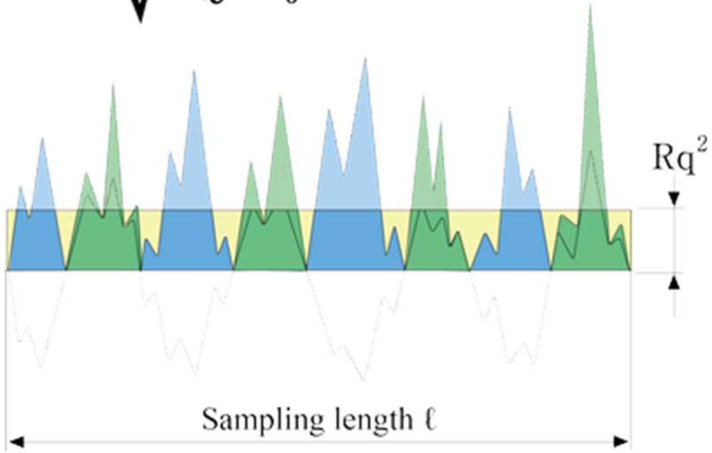
RMS is sensitive to larger peaks and valleys, where Ra is not



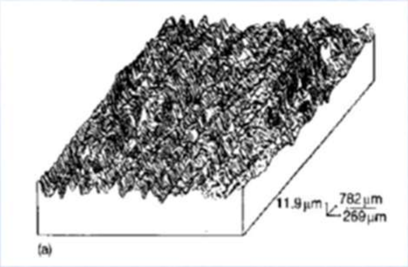
$$\mathbf{Ra} = \frac{1}{\ell}\int_0^\ell \left| Z\ (x) \right| dx$$



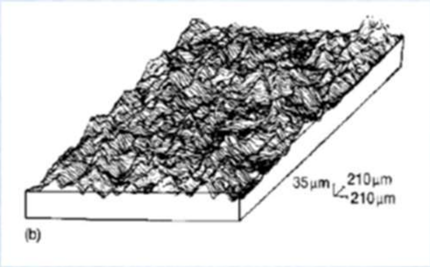
$$\mathbf{Rq} = \sqrt{\frac{1}{\ell}\int_0^\ell Z^2(x)\ dx}$$



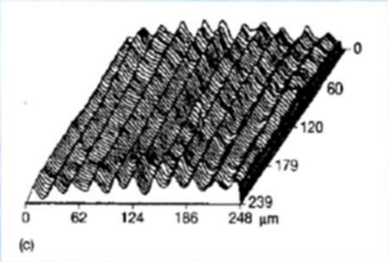
Contact of Rough Surfaces



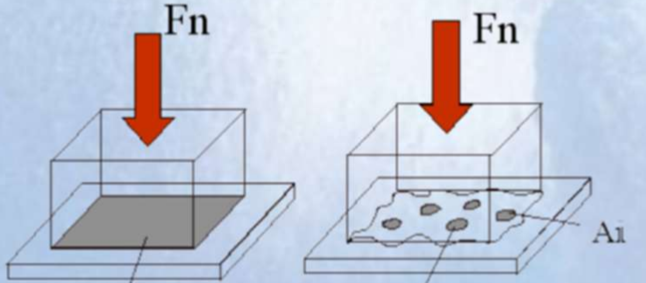
Ground steel surface



Shot-blasted steel surface



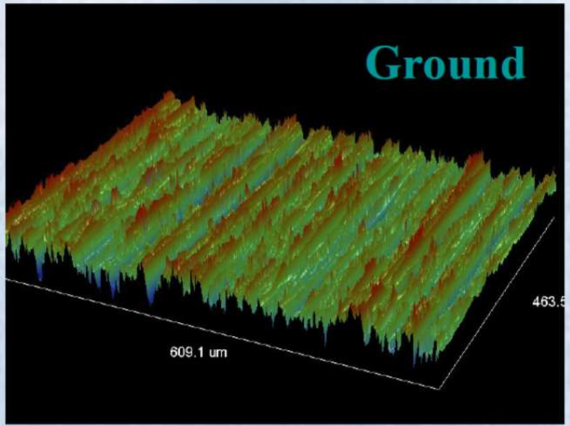
Diamond turned surface



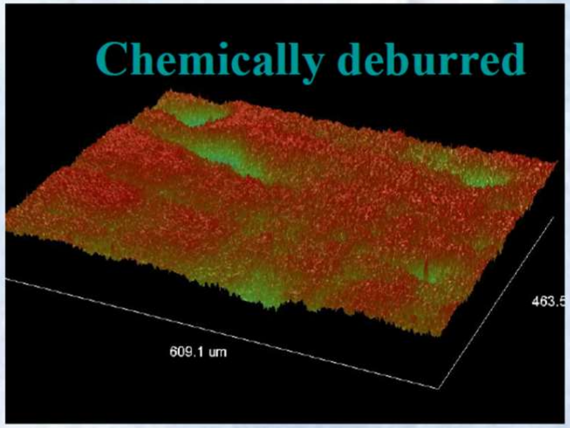
Apparent area of contact

Real area of contact

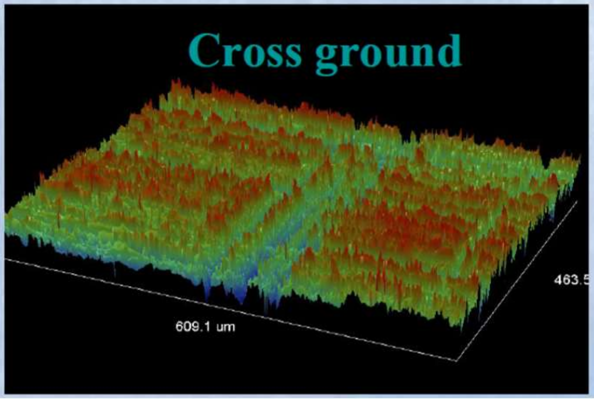
Surfaces Manufactured in Different Ways



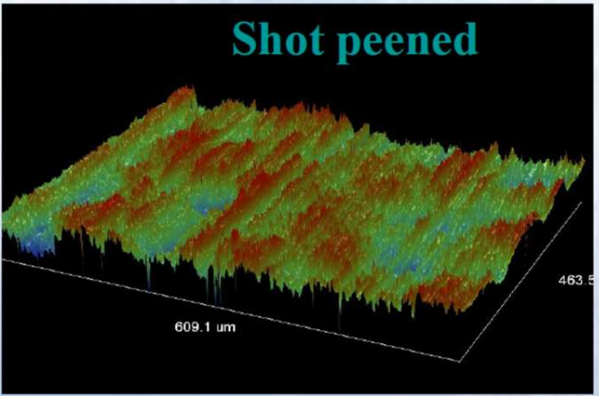
Ground



Chemically deburred



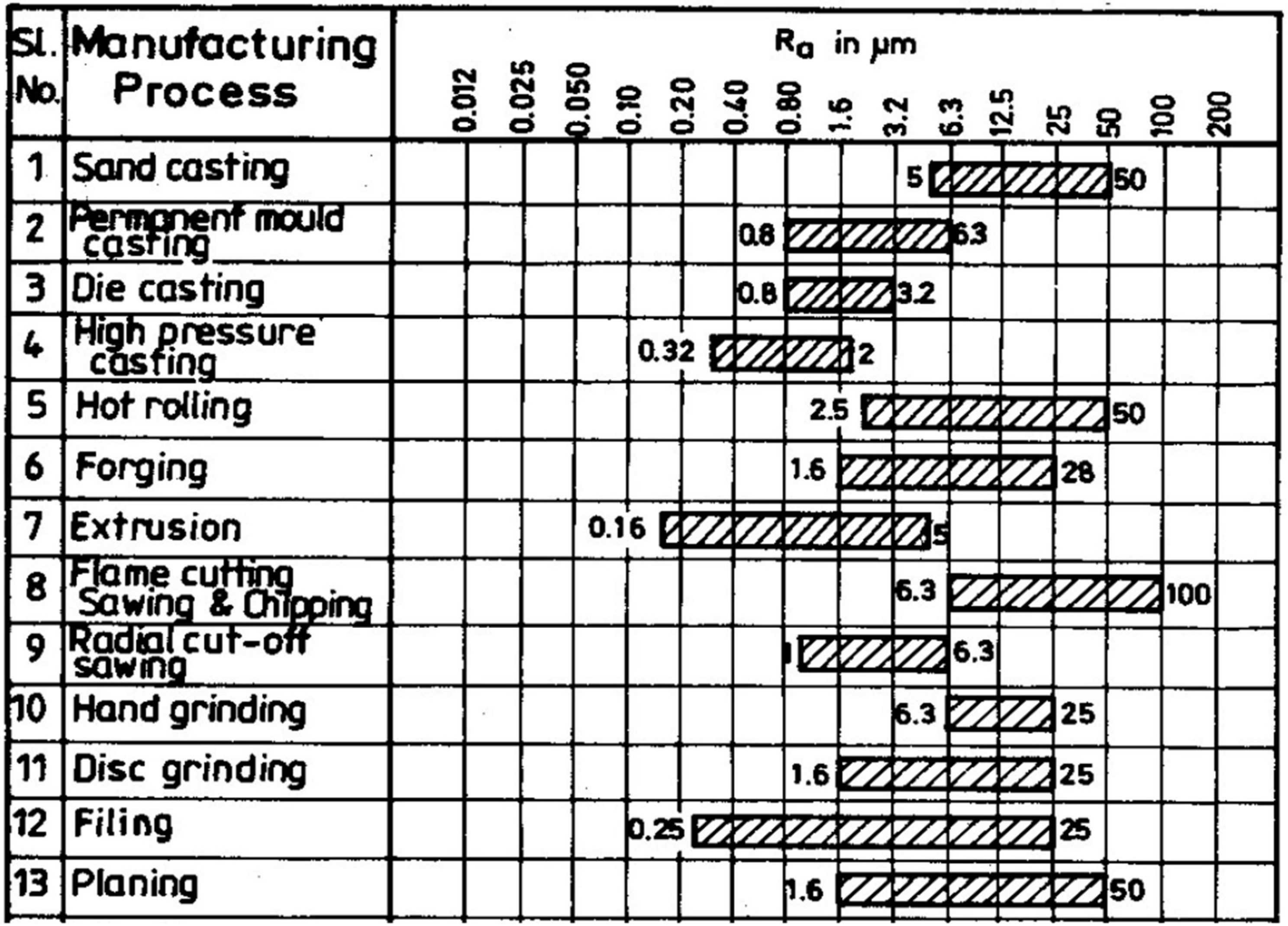
Cross ground

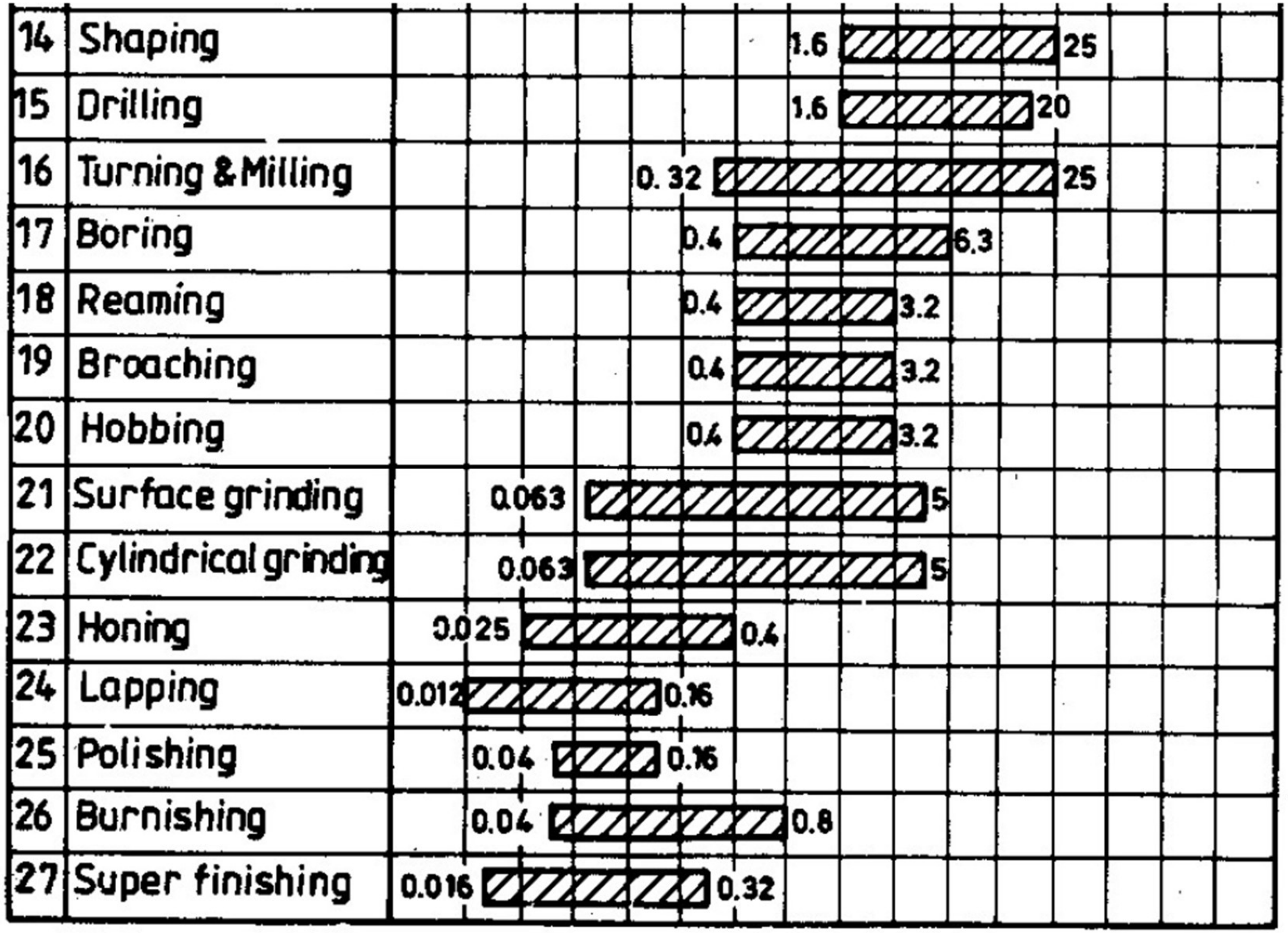


Shot peened

Typical Ra values for Engineering Surfaces

Process	**Ra (μm)**
Planing, shaping	*1-25*
Milling	*1-6*
Drawing, extrusion	*1-3*
Turning, boring	*0.4-6*
Grinding	*0.1-2*
Honing	*0.1-1*
Polishing	*0.1-0.4*
Lapping	*0.05-0.4*


Sl. No.
Manufacturing Process
Ra in µm
0.012
0.025
0.050
0.10
0.20
0.40
0.80
1.6
3.2
6.3
12.5
25
50
100
200
1 Sand casting 5 50
2 Permanent mould casting 0.8 6.3
3 Die casting 0.8 3.2
4 High pressure casting 0.32 2
5 Hot rolling 2.5 50
6 Forging 1.6 28
7 Extrusion 0.16 5
8 Flame cutting Sawing & Chipping 6.3 100
9 Radial cut-off sawing 1 6.3
10 Hand grinding 6.3 25
11 Disc grinding 1.6 25
12 Filing 0.25 25
13 Planing 1.6 50


14 Shaping 1.6 25
15 Drilling 1.6 20
16 Turning & Milling 0. 32 25
17 Boring 0.4 6.3
18 Reaming 0.4 3.2
19 Broaching 0.4 3.2
20 Hobbing 0.4 3.2
21 Surface grinding 0.063 5
22 Cylindrical grinding 0.063 5
23 Honing 0.025 0.4
24 Lapping 0.012 0.16
25 Polishing 0.04 0.16
26 Burnishing 0.04 0.8
27 Super finishing 0.016 0.32

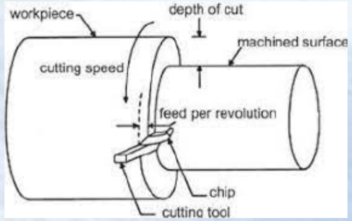
Surface Defects Caused During Manufacturing

- Crack
  internal/external
- Craters
- Folds/Seams/Laps
- Heat Affected Zone
  thermal cycling w/o melting
- Inclusions
- Residual stresses
- Splatter

- Intergranular attack
- Metallurgical transformations
  temp., press., cycling
- Plastic deformation
  worn tools
- Pits
  shallow surface depressions

The Origin of Surface Irregularities

- The production process
  - Turning
  - Grinding
  - Polishing



- The material structure
  - Brittleness
  - Atomic structure
- The use of the surfaces
  - Wear
  - Running-in
  - Corrosion

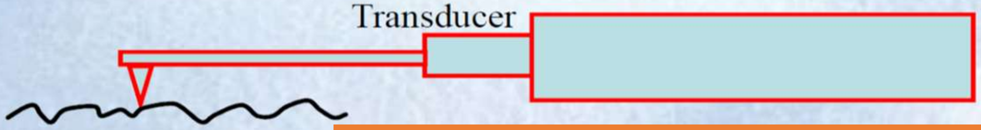
Surface Characterisation

- General features of surface
  - Appearance
  - Shape of surface
  - – Anisotropy ?
- Mechanical properties
  - Modulus
  - Yield Strength
  - Hardness
  - Toughness....
  - Stresses and strains
- Chemistry of surface
  - Elements present
  - Phase distribution

- **Localised defects**
- Any local changes in
  - Shape
  - Mechanical properties
  - Chemistry
- Cracks

Surface Topography Measurement Methods

- Stylus profilometers (2D+1D)



Interferometry' is a measurement method using the phenomenon of interference of waves (usually light, radio or sound waves).

- Optical methods (3D)
  - Interferrometry
- Scanning probe microscopy (2D+1D)
  - Scanning tunneling microscopy (STM)
  - Atomic force microscopy (AFM)

Surface topography measurements are never exact. All different Techniques give different answers. Even the use of the same technique at different laboratories!

Stylus profilometer

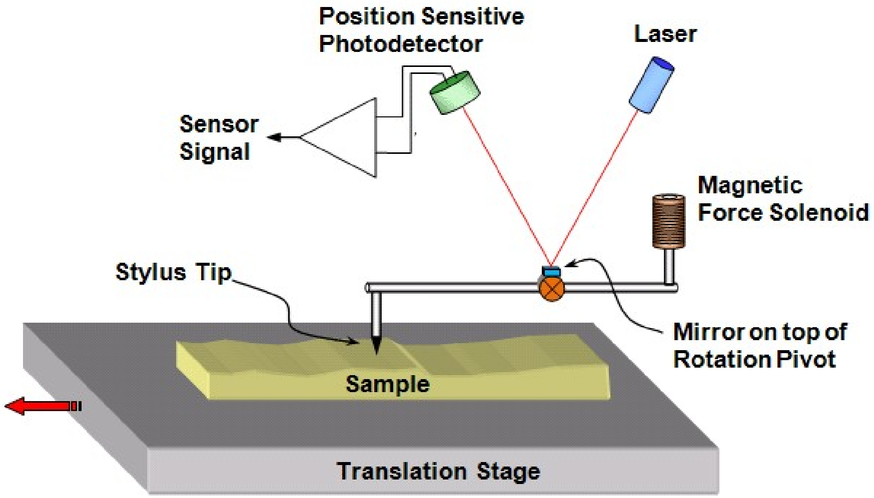
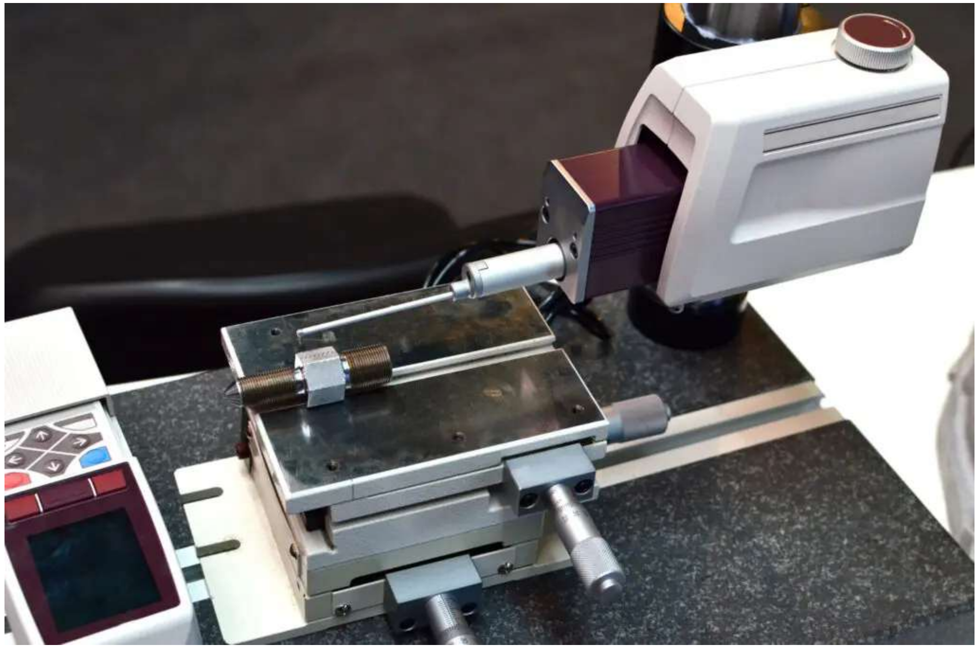


Figure 1 Basic elements of a stylus profilometer.



AFM versus STM

- AFM provides high-resolution topographic images and information on sample mechanics, making it ideal for imaging delicate biological samples, polymers, and insulators.
- STM excels at atomic-scale electronic characterization of flat conductive surfaces like metals, semiconductors, or graphene.

Problems Encountered in Surface Topography Measurements

- **Stylus profilometers**
  - The tip radius (a few μm) is too large to resolve very fine irregularities
  - Might damage the surface (replication might be the solution)
- **Optical methods**
  - Expensive equipment
  - Thin films on the surface might cause errors
- **Scanning probe microscopy**
  - Expensive and sensitive equipment
  - Measurement on very small areas might lead to mis-interpretations

General Remarks

Considering the complexity of the tribological system, it may be pertinent to point out that friction and wear characteristics of materials are not their intrinsic or inherent properties but are highly system dependent.

Some of the Basic Questions
What is friction?

How is the friction force generated?

What is the coefficient of friction?

How do materials wear?

What is the effect of the applied load on friction and wear?
What is the role of lubricant?

How do you lower friction?
How should we reduce the wear rate of materials?

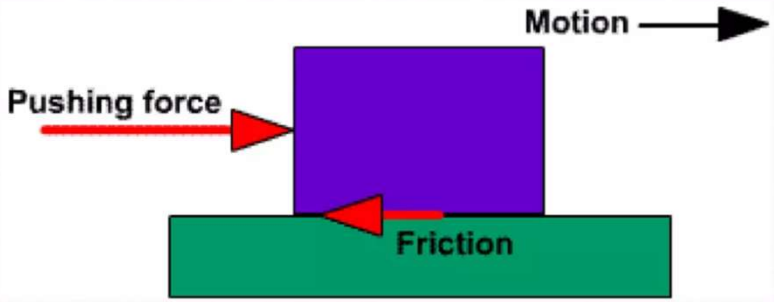
Friction

Content

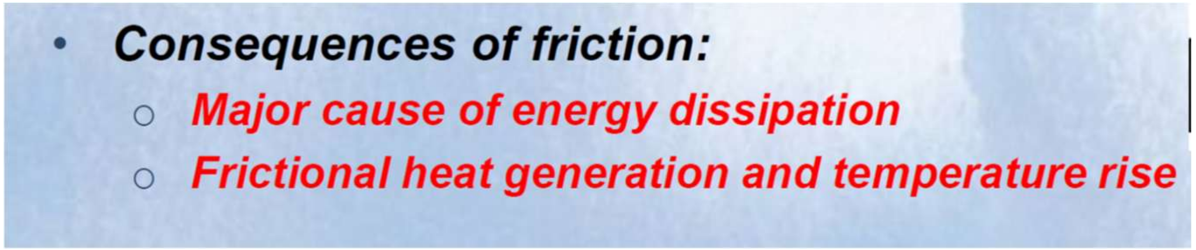
- What is Friction?
- Type of Friction
- Co-efficient of Friction
- Laws Of Friction

What Is Friction?

- When a body slide or tends to slide on a surface on which it is resting, a resisting force opposing the motion is produced at the contact surface. This resisting force is called friction or friction force.



- When one solid body is slide over another there is a resistance to the motion which is called friction.
- Considering friction as a nuisance, attempts are made to eliminate it or to diminish it to as small a value as possible.
- Considerable loss of power is caused by friction (e.g. about 20% in motor cars, 9% in airplane piston engine and (1 ½ -2)% in turbojet engines) but more important aspect is the damage that is done by friction – the WEAR of some vital parts of machines.
- This factor limits the design and shortens the effective working life of the machines.

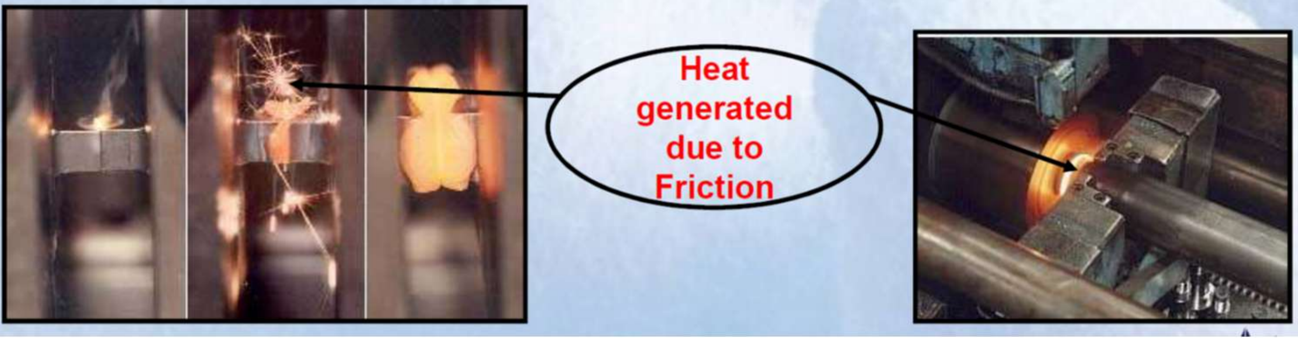


- ***Consequences of friction:***
  - ***Major cause of energy dissipation***
  - ***Frictional heat generation and temperature rise***

Friction

INTRODUCTION…..(Cont…)

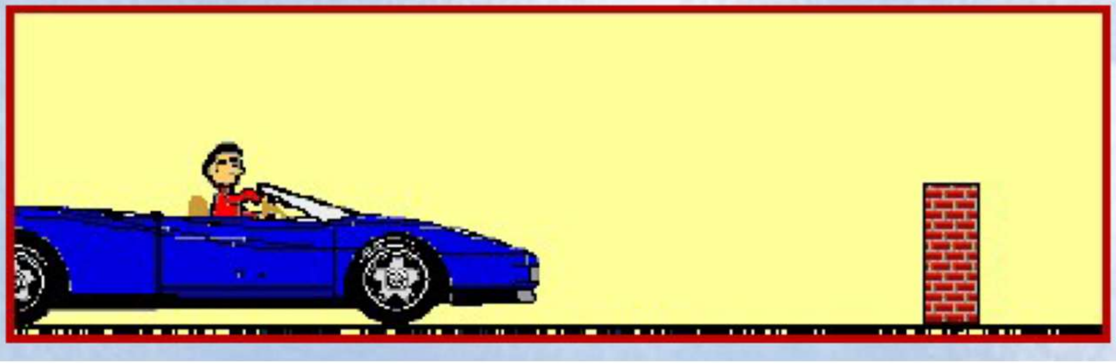
- On the other hand, in most of running machines friction is undesirable (energy loss, leading to wear of vital parts, deteriorating performance due to heat generation) and all sorts of attempts (i.e. using low friction materials, lubricating surfaces with oil or greases, changing design so that sliding can be reduced) have been made to reduce it.



Heat generated due to Friction

- Many people think that it is a nuisance because it has causes us to apply a greater force to move an object.
- But in fact, it is of great help to us.

- **If there is no friction, then cars cannot move on the road and we can hardly even walk.**



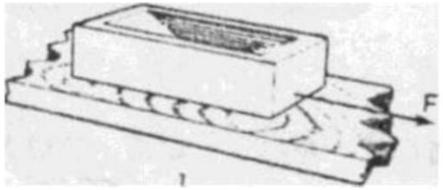
Friction

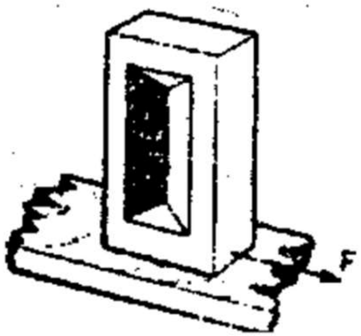
- ***We encounter friction in all aspects of everyday lives:***
- ***Walking***
- ***Moving***
- ***Stopping or turning a car***

❖ It is needed so that we have control on our walking.

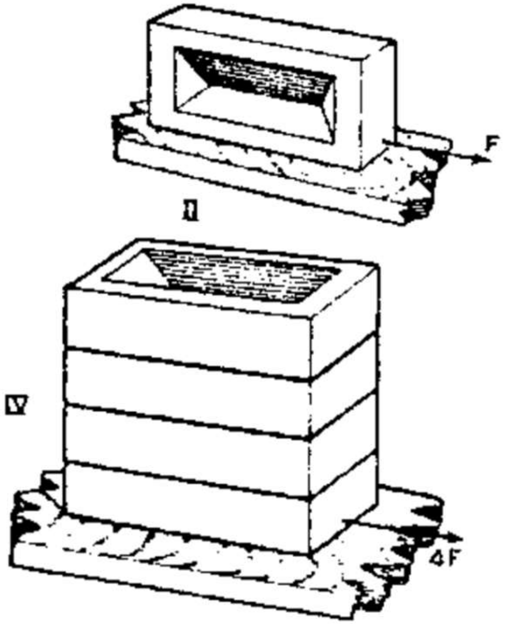
Laws of Friction

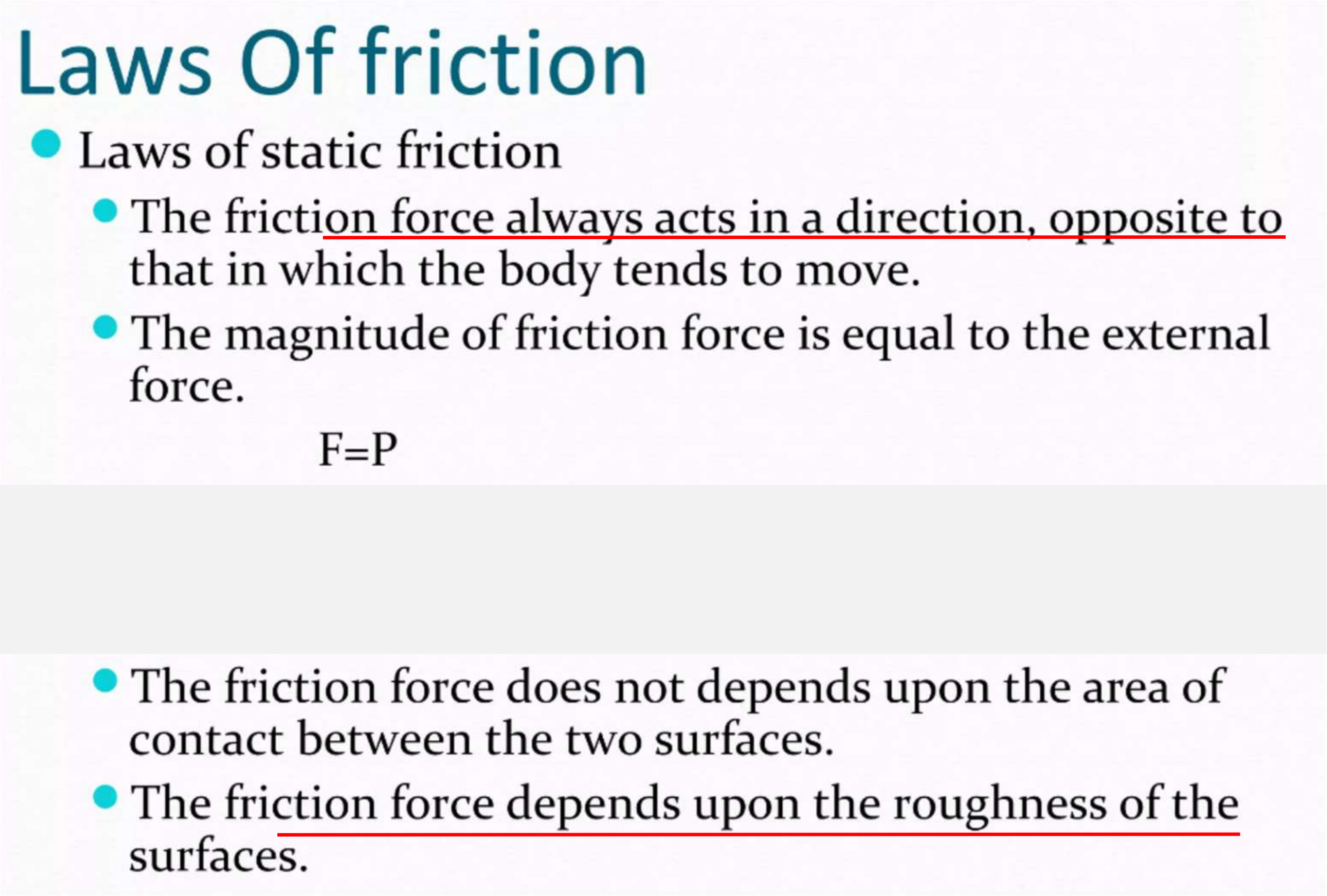
- First Law: The friction is independent of the area of contact between the solids .
- For example; if one pulls a brick along a table, the friction is same whether the brick is lying flat, or on its side, or standing on its end





- Second Law: The friction is proportional to the load between the surfaces
- e.g. if the load is doubled by putting a second brick on top of first, the force required to cause sliding is twice as great. If a pile of four bricks is used, the friction would be four times as great, and so on





Laws Of friction

- Laws of static friction
  - The friction force always acts in a direction, opposite to that in which the body tends to move.
  - The magnitude of friction force is equal to the external force.

$$F=P$$

  - The friction force does not depends upon the area of contact between the two surfaces.
  - The friction force depends upon the roughness of the surfaces.

What is friction?

- Friction is a result of energy dissipation at the (sliding) interface.

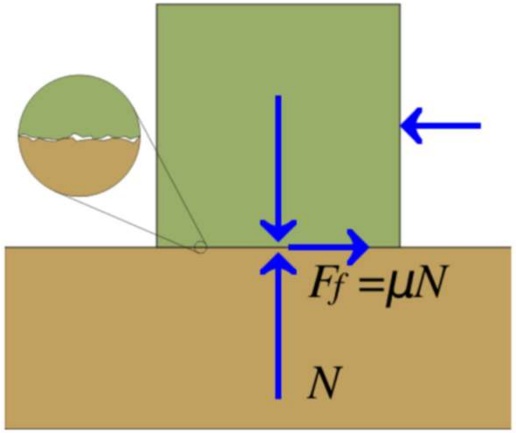
Friction force

$$f = \mu N$$

f = friction force

μ = coefficient of friction

N = normal force



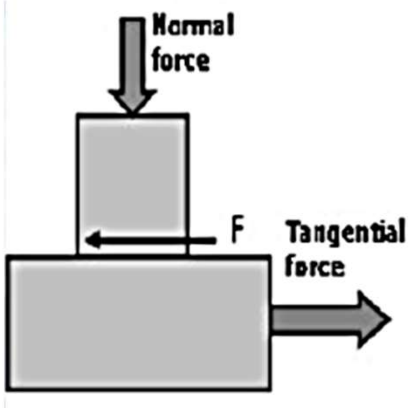
What is the coefficient of friction?

Coefficient of friction(COF), the ratio of the frictional force resisting the motion of two surfaces in contact to the normal force pressing the two surfaces together.

- Friction coefficient is defined as

μ = Friction / Load

$$\mu = \frac{\text{Tangential force}}{\text{Normal load}}$$



- Is it a material property?

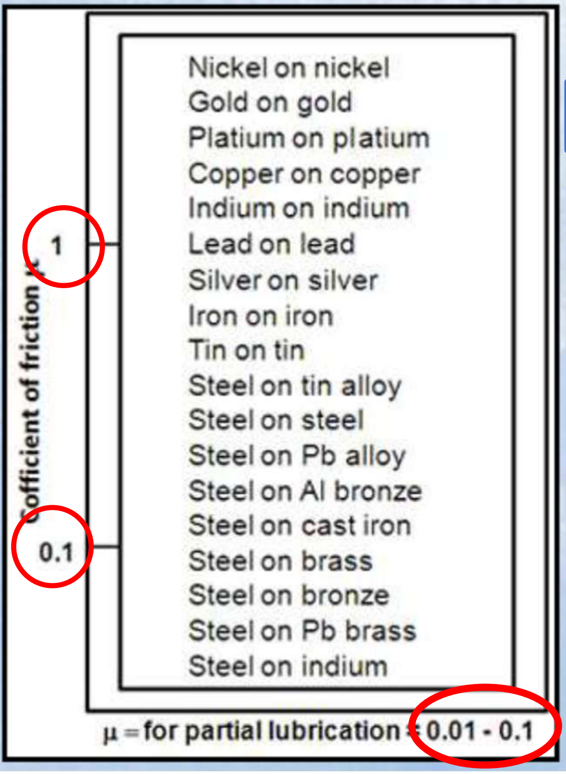
- It may be noted that μ varies widely for different solids.

- **Example:** For a case of a brick sliding over a clean wooden table $\mu = 0.5$, i.e. force equal to one-half of the weight of the brick is required to pull it along.

  For ice sliding on ice, $\mu = 0.02 – 0.03$ & For copper sliding over copper, $\mu = 0.8$ to 1.0,

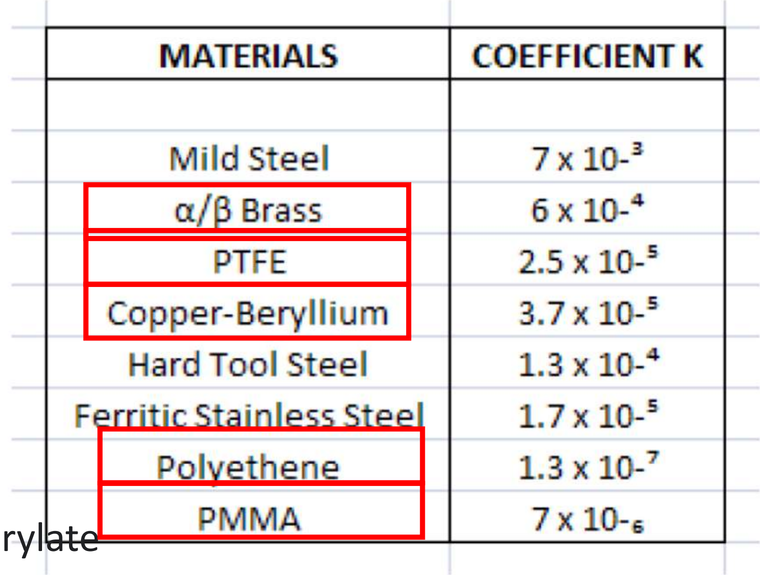
Friction

- Fig. indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.



For homework

Fig. : Coefficient of friction for various metals.



MATERIALS	COEFFICIENT K
Mild Steel	7 x 10-^{3}
α/β Brass	6 x 10-^{4}
PTFE	2.5 x 10-^{5}
Copper-Beryllium	3.7 x 10-^{5}
Hard Tool Steel	1.3 x 10-^{4}
Ferritic Stainless Steel	1.7 x 10-^{5}
Polyethene	1.3 x 10-^{7}
PMMA	7 x 10-$_{6}$

Polymethyl methacrylate

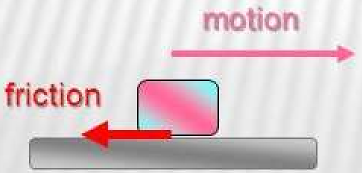
TABLE 2: COEFFICIENT OF WEAR (ω) FOR VARIOUS MATERIALS

Experimental facts characterize the friction of sliding solids:

- Friction opposes motion
- Friction is dependent on the texture of the surfaces
- Friction is dependent on normal force

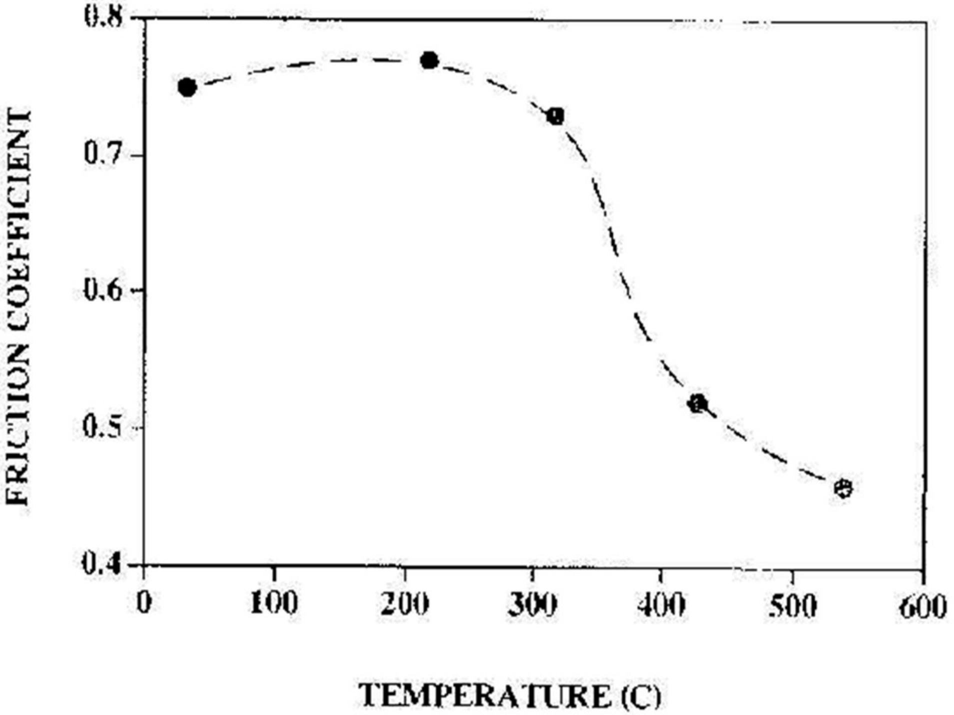
$F_{fr} = \mu F_n$ ***μ*** **is called coefficient of friction**

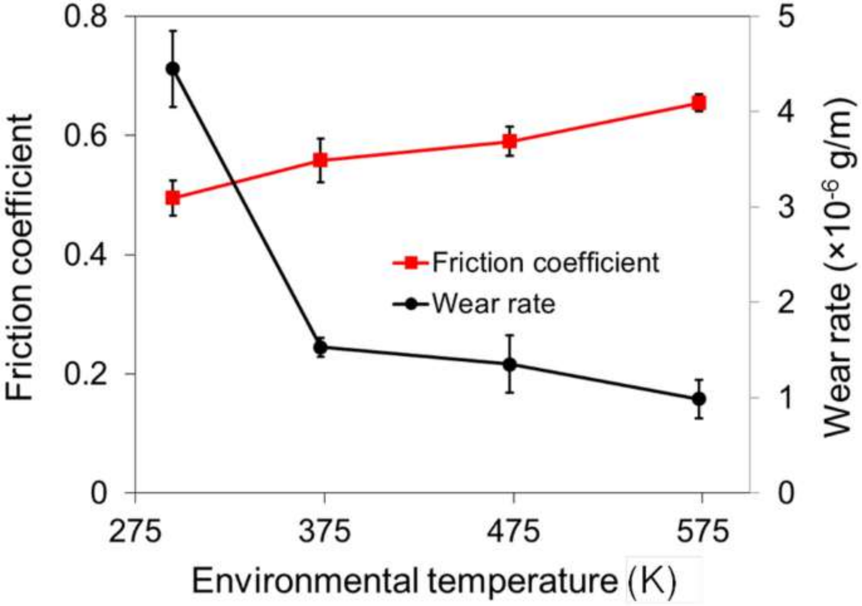
◆ μ has no units
◆ depends on characteristics of both surfaces
◆ Higher μ = rougher surface / more friction



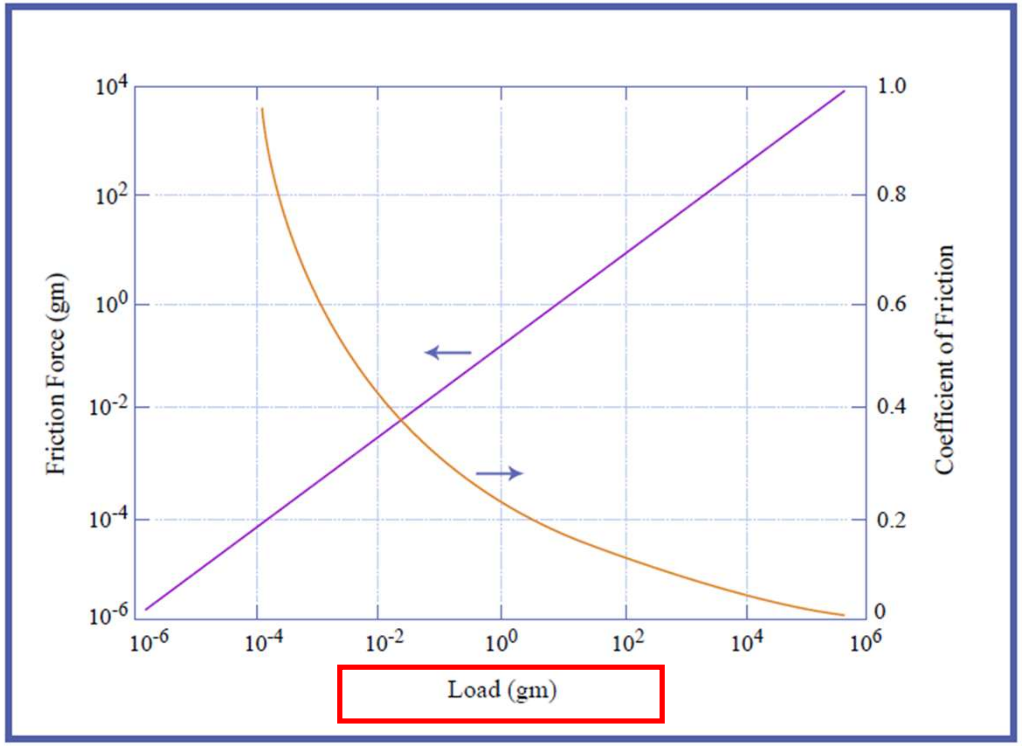
Note: Friction does NOT depend on the surface area of contact

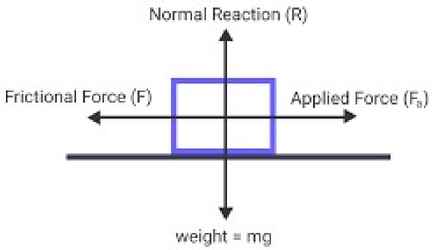
Is the friction coefficient constant?





Is the friction coefficient constant?





$$f = \mu N$$

μ = Friction / Load

Is the friction coefficient constant?

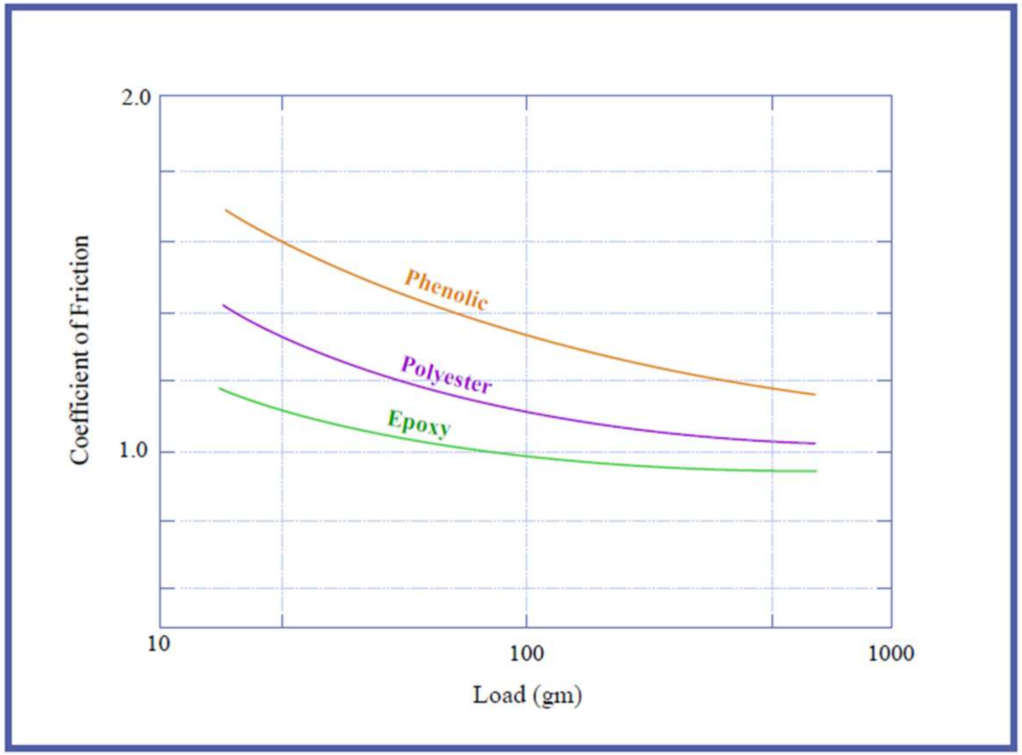
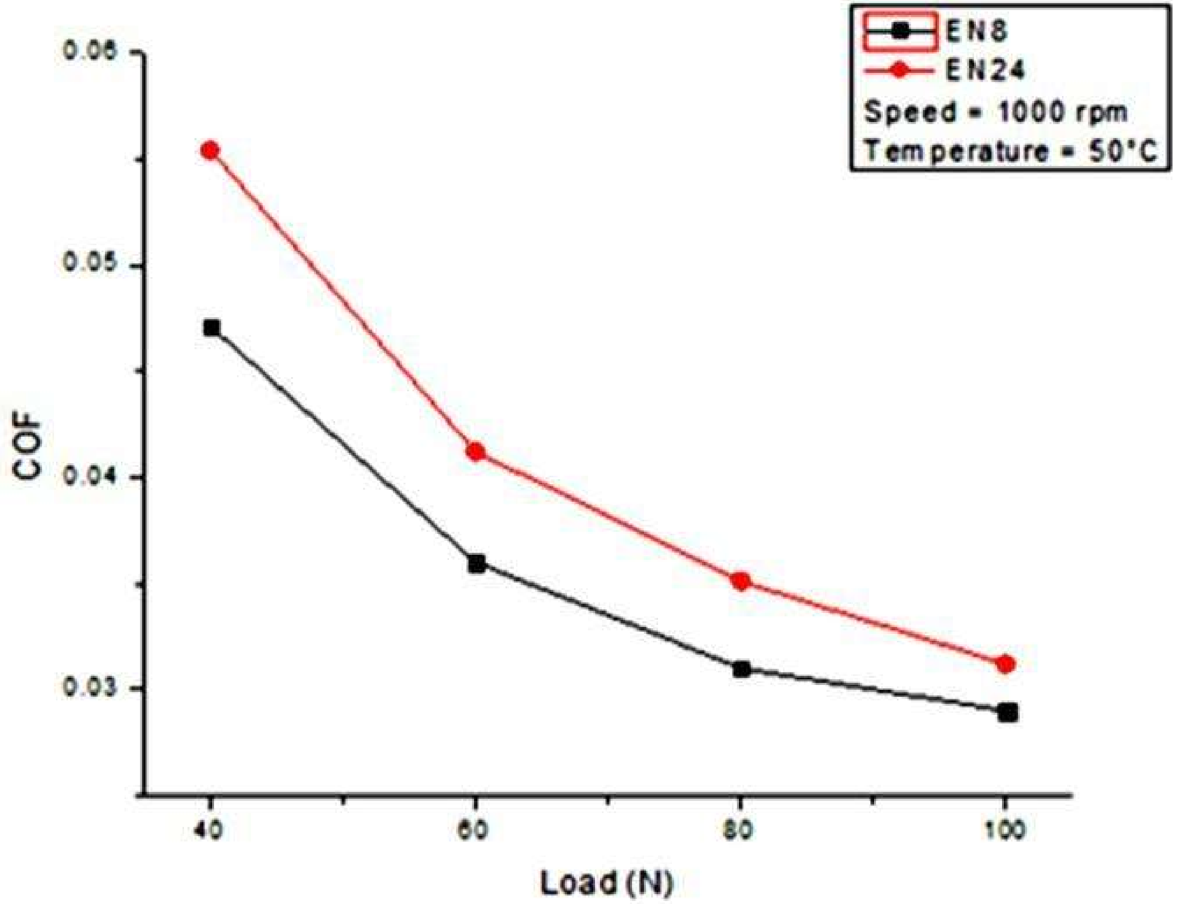
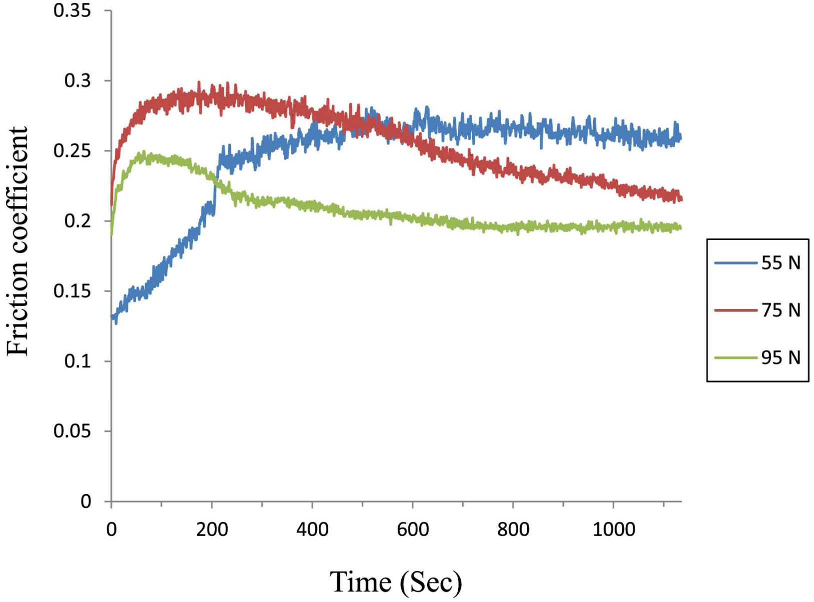


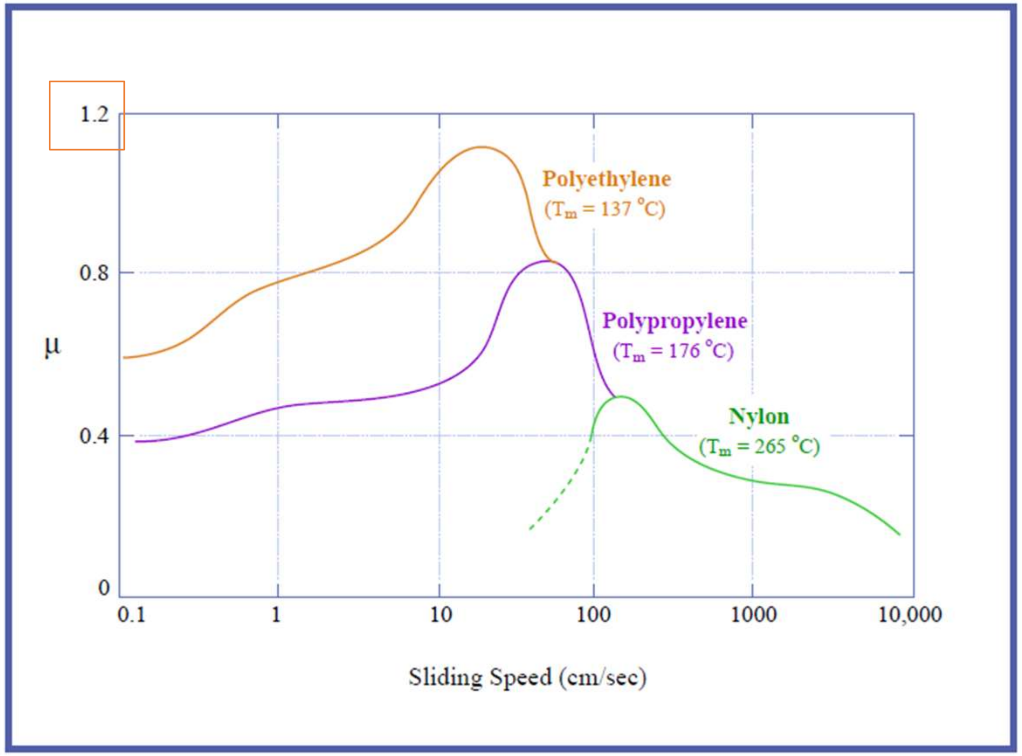
Figure by MIT OCW. After Pinchibeck, P. H. "A Review of Plastic Bearings." *Wear* 5 (1962): 85-113.

Is the friction coefficient constant?





Is the friction coefficient constant?



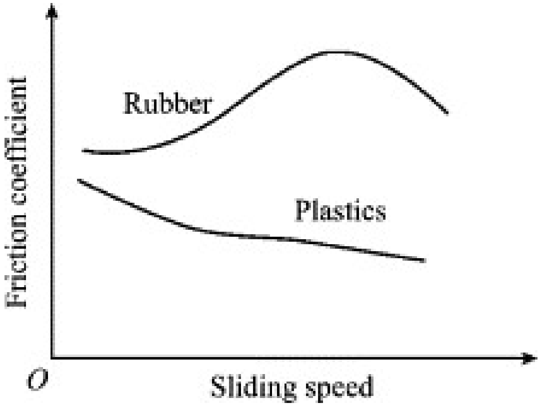
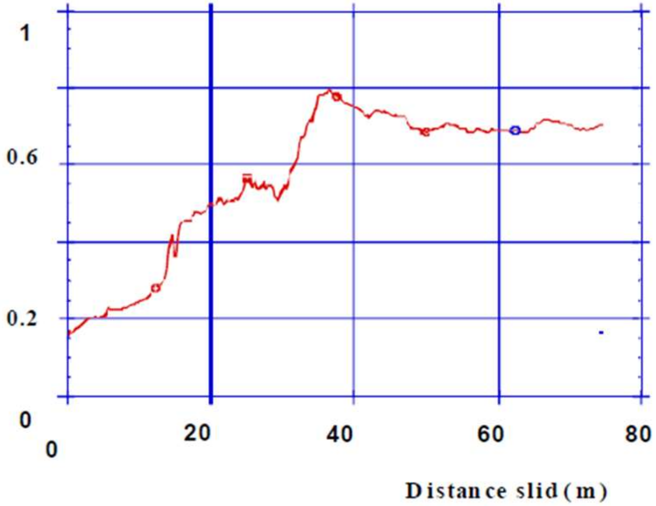


Figure by MIT OCW. After McLaren and Tabor, 1963.

Is the friction coefficient constant?

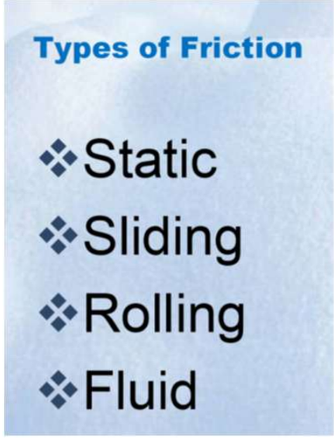


Types of friction:

- Dry friction
- Fluid friction
- Lubricated friction
- Skin friction (Fluid and solid)
- Internal friction (Solids)

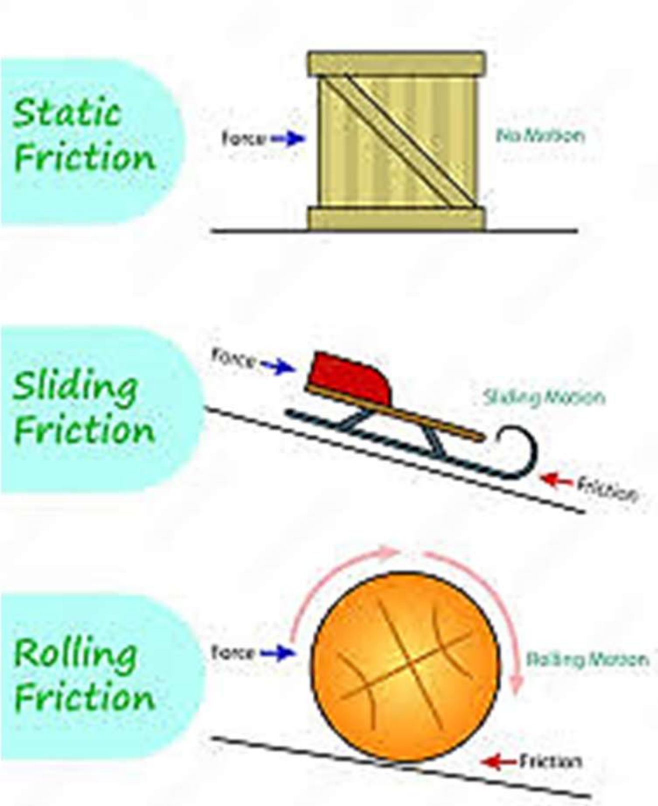
Dry or Coulombic friction

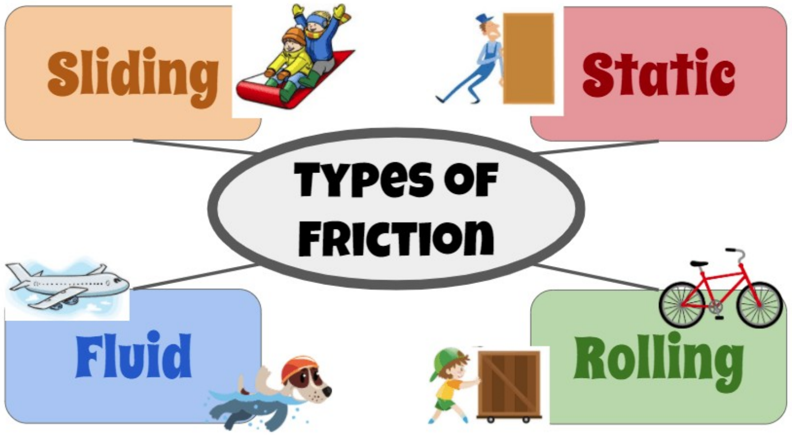
Types of friction:



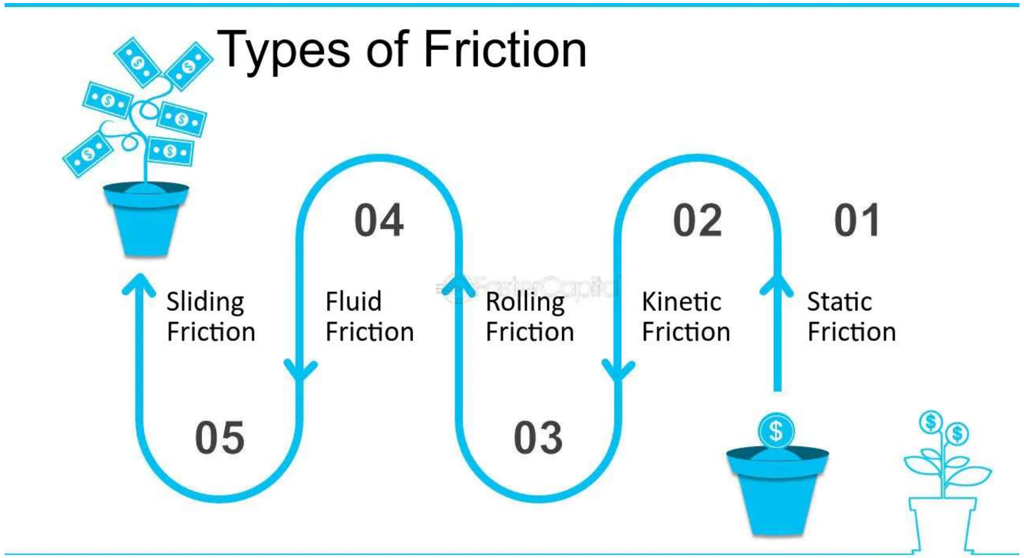
Types of Friction

- Static
- Sliding
- Rolling
- Fluid





Types of friction:



1. Static Friction

Static friction is the friction that exists between two objects that are not moving relative to each other. It is the force that must be overcome to set an object in motion. Static friction is essential in many everyday activities, such as walking, driving, and even writing. For example, when you push a book across a table, static friction keeps the book from sliding off the table.

2. Kinetic Friction

Kinetic friction is the friction that exists between two objects that are moving relative to each other. It is the force that opposes the motion of an object that is already in motion. *Kinetic friction* is present in *many everyday activities*, such as riding a bike or driving a car. For example, when you brake while driving, the kinetic friction between *the brake pads* and the wheels slows down the car.

Static and Kinetic Friction

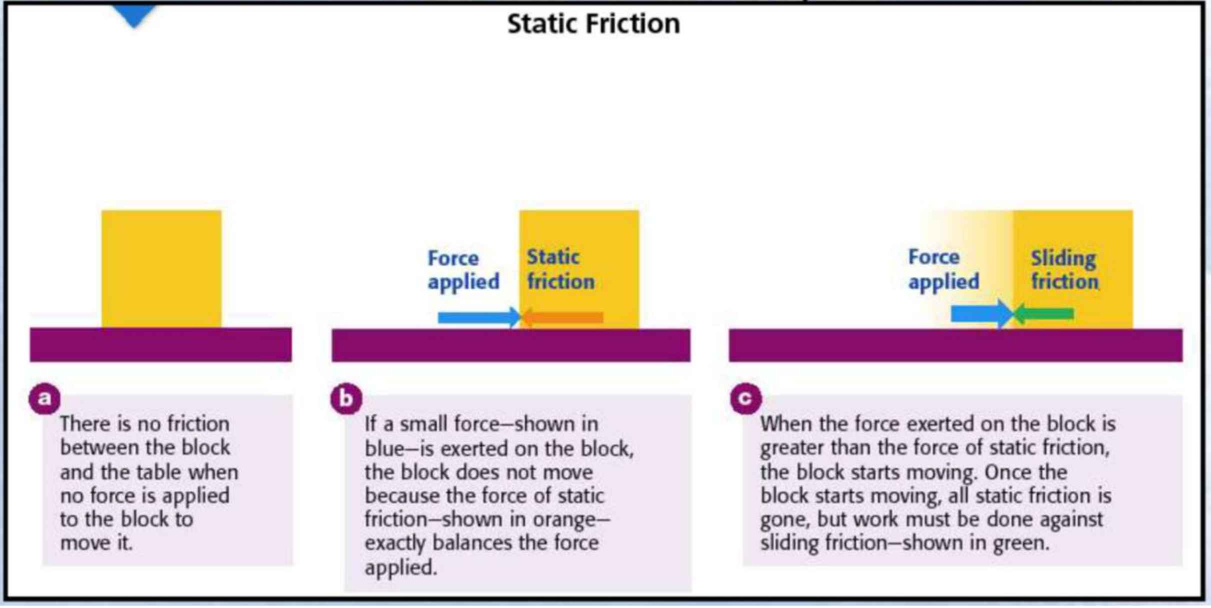
- Static friction is the force required to start sliding.

Dynamic Friction

- kinetic friction is the force required to maintain it.
- It is known that kinetic friction is less than the static friction and kinetic friction is nearly independent of the speed of sliding.

Static Friction

- In this figure, a horizontal force is applied to a body with an intention to move it to the right-side. (note: if the force applied is too small the “static friction is greater and the block will not move.)



Static Friction

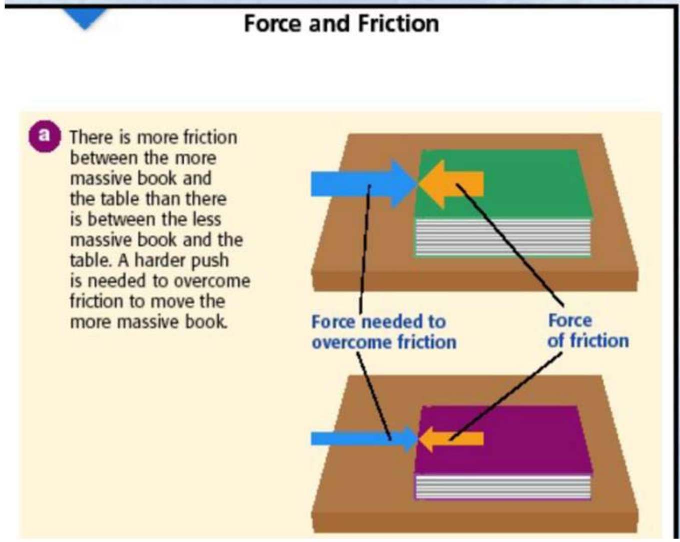
a There is no friction between the block and the table when no force is applied to the block to move it.

b If a small force—shown in blue—is exerted on the block, the block does not move because the force of static friction—shown in orange—exactly balances the force applied.

c When the force exerted on the block is greater than the force of static friction, the block starts moving. Once the block starts moving, all static friction is gone, but work must be done against sliding friction—shown in green.

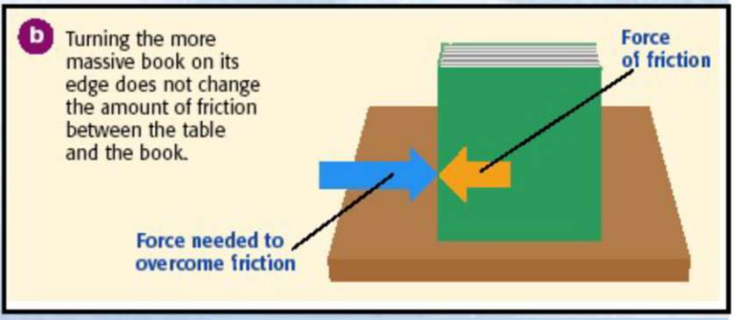
Greater Mass
Creates More Friction

A greater push is needed to overcome the greater mass which has greater (static) friction

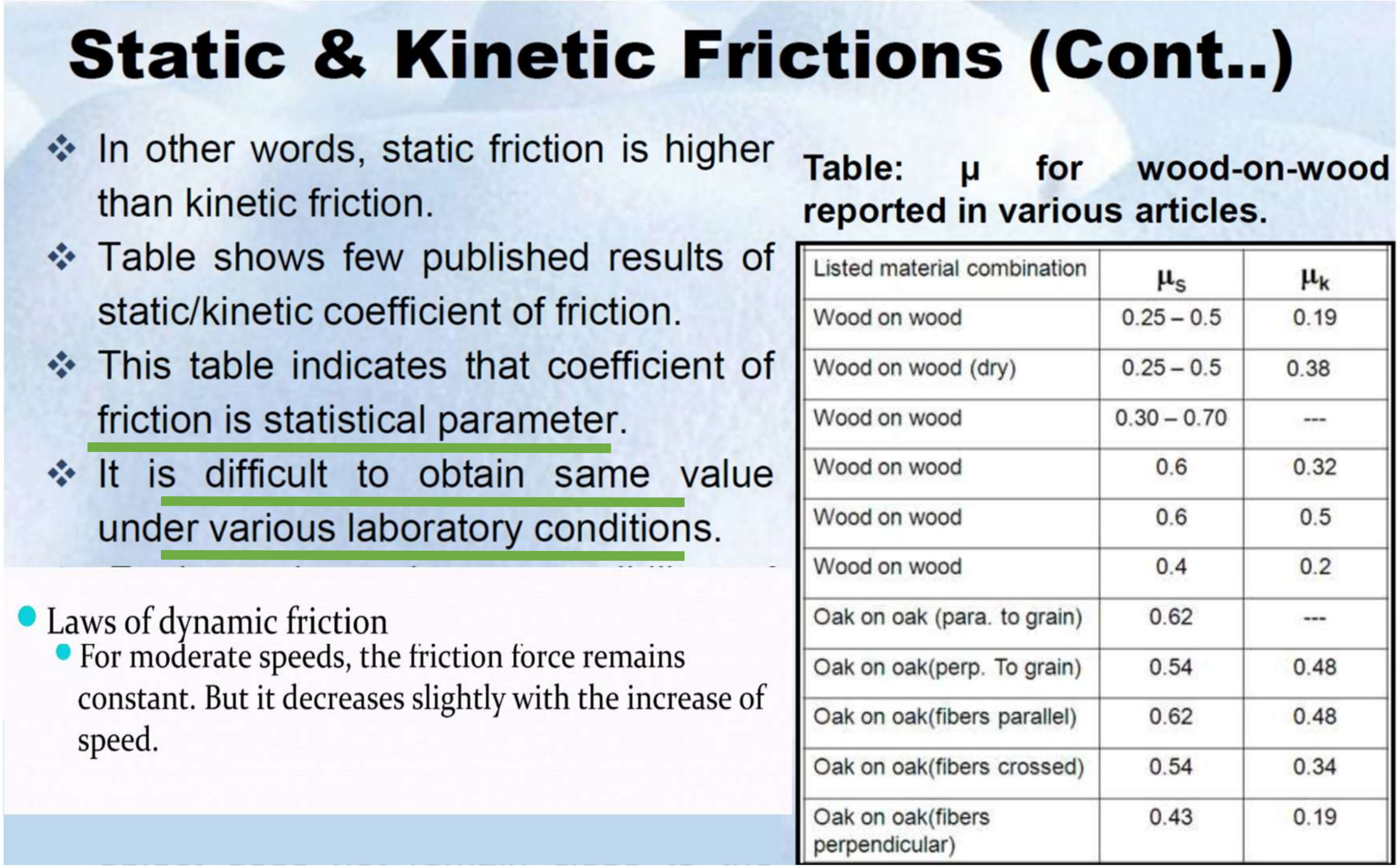


Force and Friction

a There is more friction between the more massive book and the table than there is between the less massive book and the table. A harder push is needed to overcome friction to move the more massive book.



b Turning the more massive book on its edge does not change the amount of friction between the table and the book.



Static & Kinetic Frictions (Cont..)

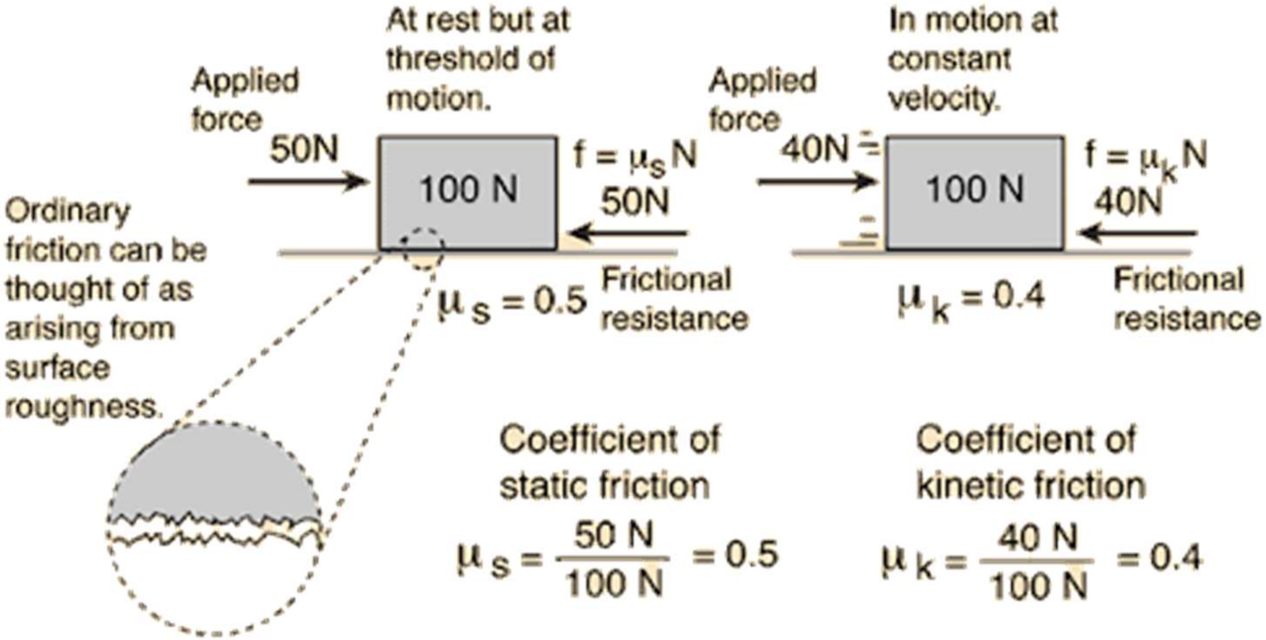
- ❖ In other words, static friction is higher than kinetic friction.
- ❖ Table shows few published results of static/kinetic coefficient of friction.
- ❖ This table indicates that coefficient of friction is statistical parameter.
- ❖ It is difficult to obtain same value under various laboratory conditions.

- Laws of dynamic friction
  - For moderate speeds, the friction force remains constant. But it decreases slightly with the increase of speed.

Table: μ for wood-on-wood reported in various articles.

Listed material combination	μ_s	μ_k
Wood on wood	0.25 – 0.5	0.19
Wood on wood (dry)	0.25 – 0.5	0.38
Wood on wood	0.30 – 0.70	---
Wood on wood	0.6	0.32
Wood on wood	0.6	0.5
Wood on wood	0.4	0.2
Oak on oak (para. to grain)	0.62	---
Oak on oak(perp. To grain)	0.54	0.48
Oak on oak(fibers parallel)	0.62	0.48
Oak on oak(fibers crossed)	0.54	0.34
Oak on oak(fibers perpendicular)	0.43	0.19

Coefficient of friction(COF)



Sliding and rolling

3. Sliding Friction

Sliding friction is the friction that exists between two objects that are sliding against each other. It is the force that opposes the motion of an object that is sliding. *Sliding friction* is present in *many everyday activities*, such as sliding a drawer. For example, when you slide a drawer, the sliding friction between the drawer and the frame keeps the drawer from falling out.

Rolling

4. Rolling Friction

Rolling friction is the friction between a rolling object and the surface it is rolling on. It is the force that opposes the motion of an object that is rolling. Rolling friction is present in many everyday activities, such as riding a bike or driving a car. For example, when you ride a bike, the friction between the wheels and the road keeps the bike moving forward.

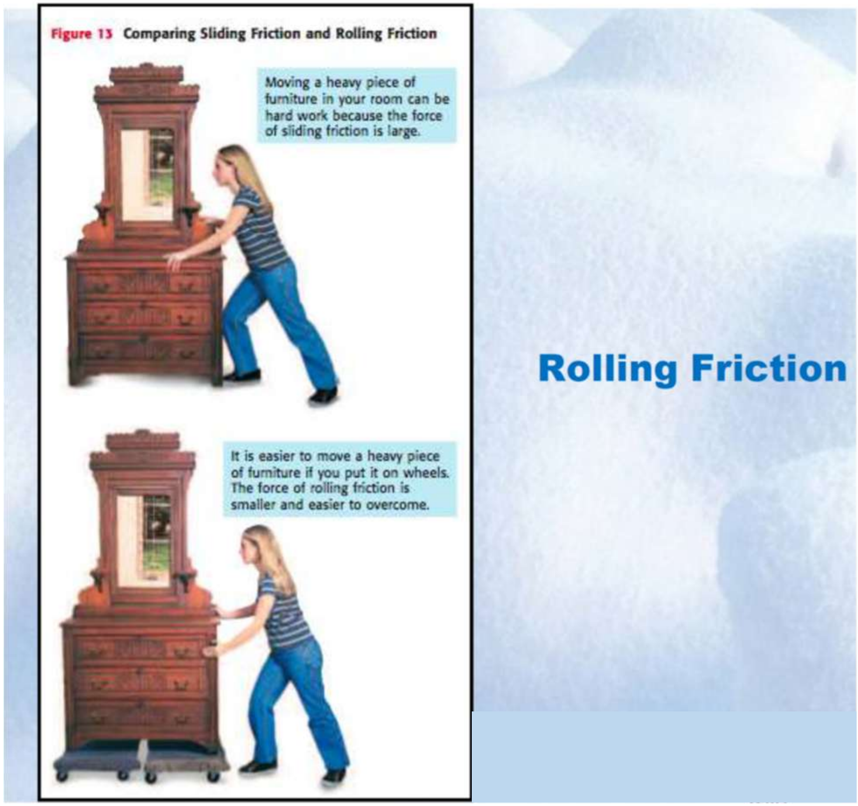


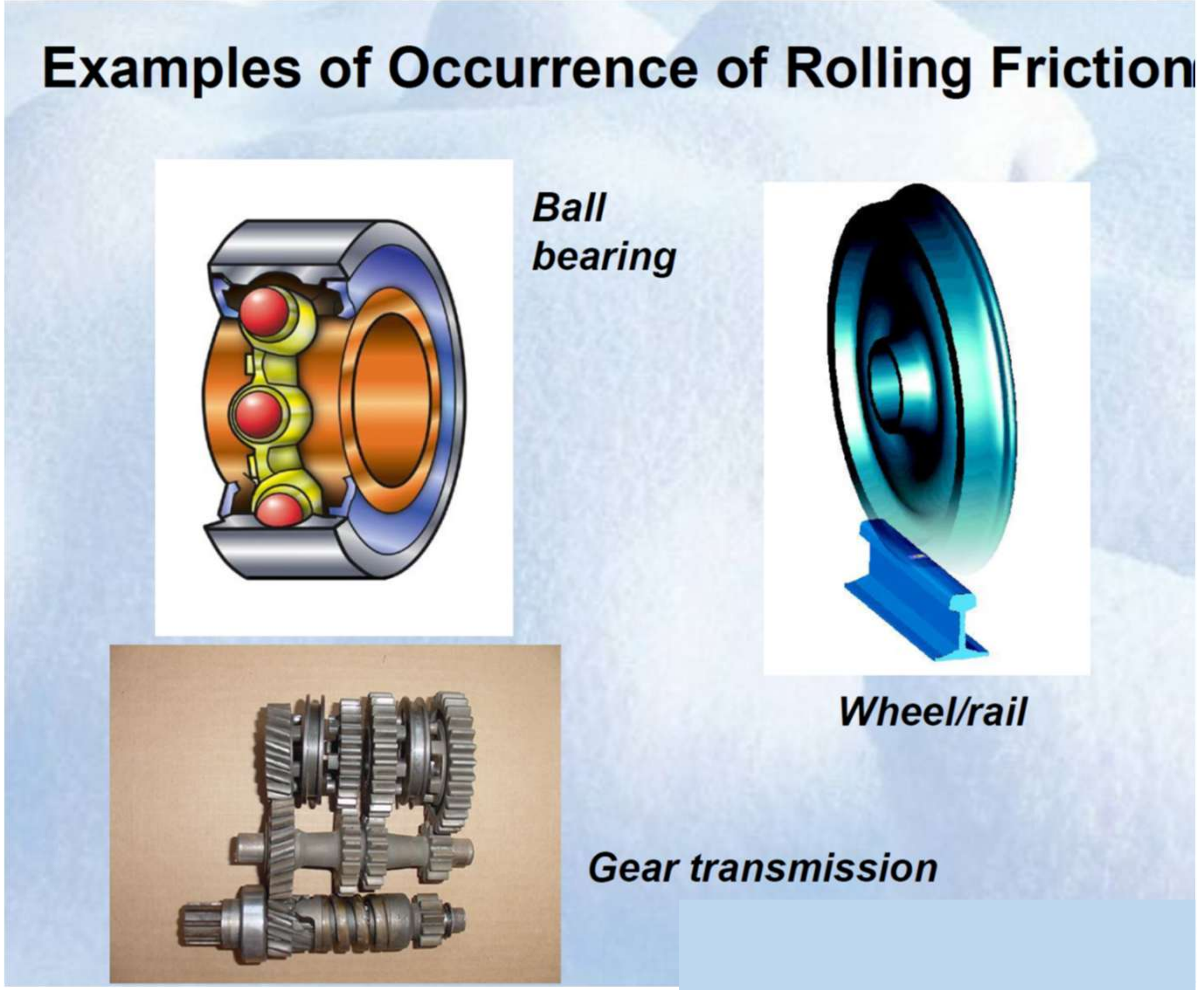
Figure 13 Comparing Sliding Friction and Rolling Friction

Moving a heavy piece of furniture in your room can be hard work because the force of sliding friction is large.

It is easier to move a heavy piece of furniture if you put it on wheels. The force of rolling friction is smaller and easier to overcome.

Rolling Friction

Rolling



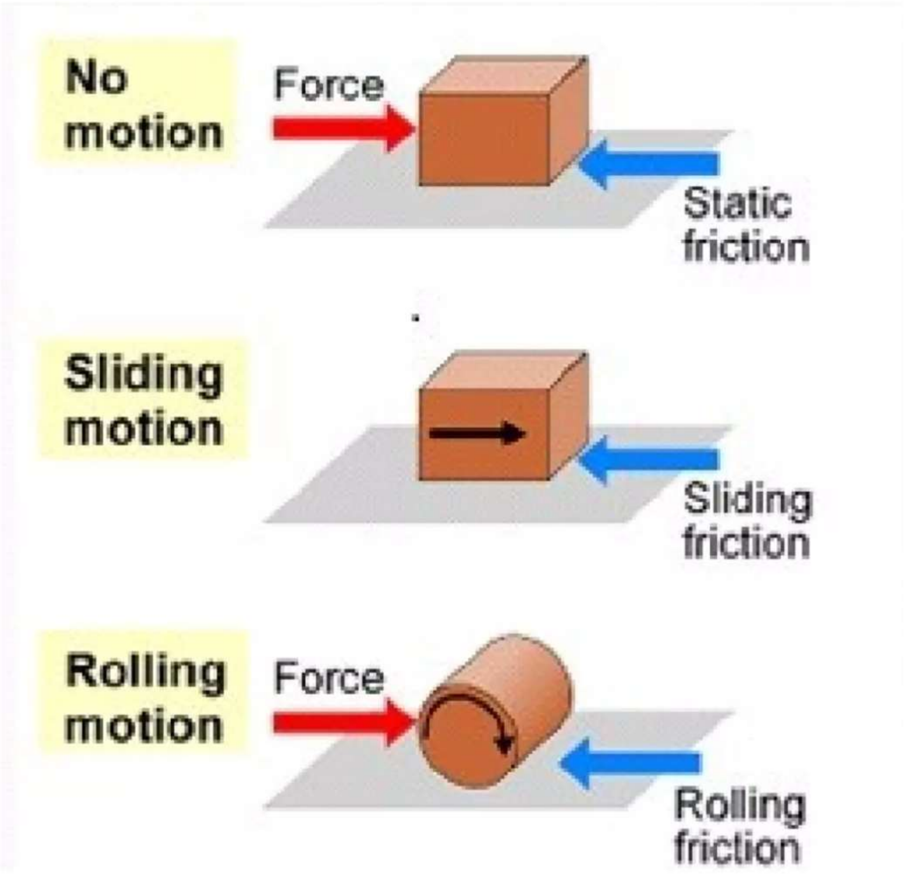
Examples of Occurrence of Rolling Friction

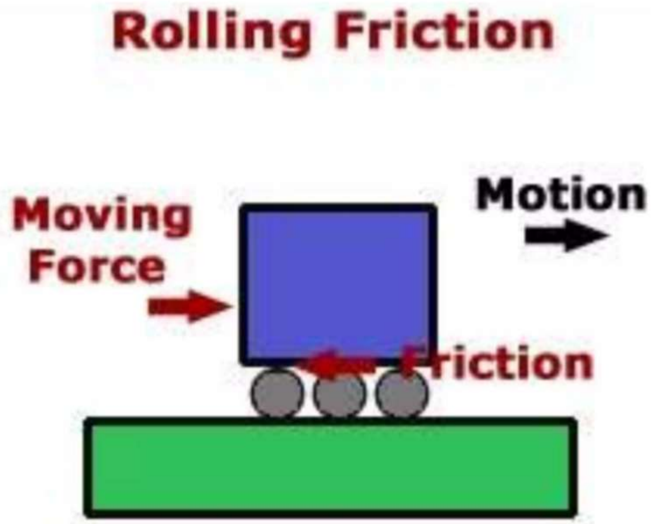
Ball bearing

Wheel/rail

Gear transmission

Sliding and rolling





ROLLING FRICTION

Types of Rolling :

- The first type of rolling occurs when a car wheel is driven over a road or a train wheel over a rail. Here considerable tangential forces are involved in pulling the vehicle along, and the conventional frictional grip between the wheel and the surface is of great importance.
- The other type of rolling involves only a minute tangential traction i.e. the rolling that occurs when a ball or cylinder rolls freely over another surface called free rolling which is most commonly applied in ball bearings and roller bearings.

5.Fluid Friction

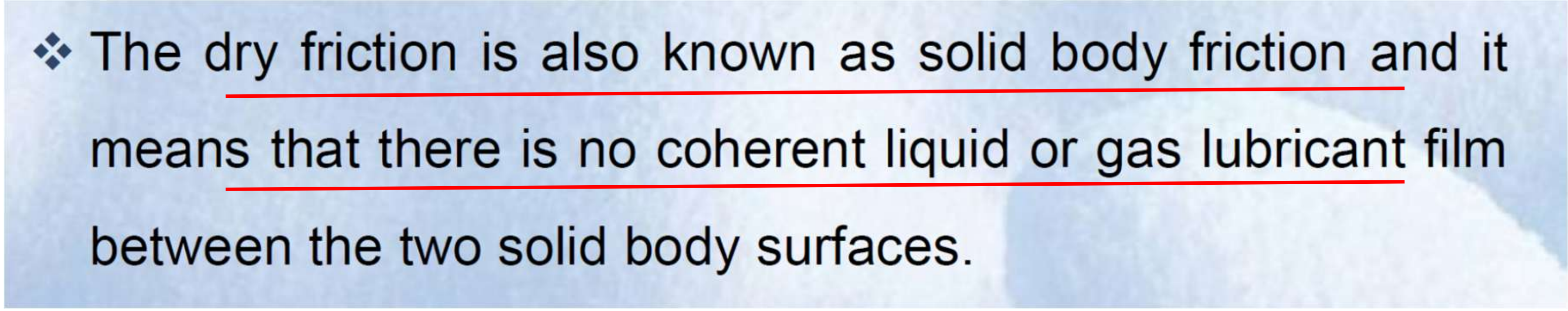
- Fluid friction opposes the motion of objects traveling through a fluid

- Remember that fluids include liquids & gases, water, milk and air are ALL fluids

Figure 14 *Swimming provides a good workout because you must exert force to overcome fluid friction.*

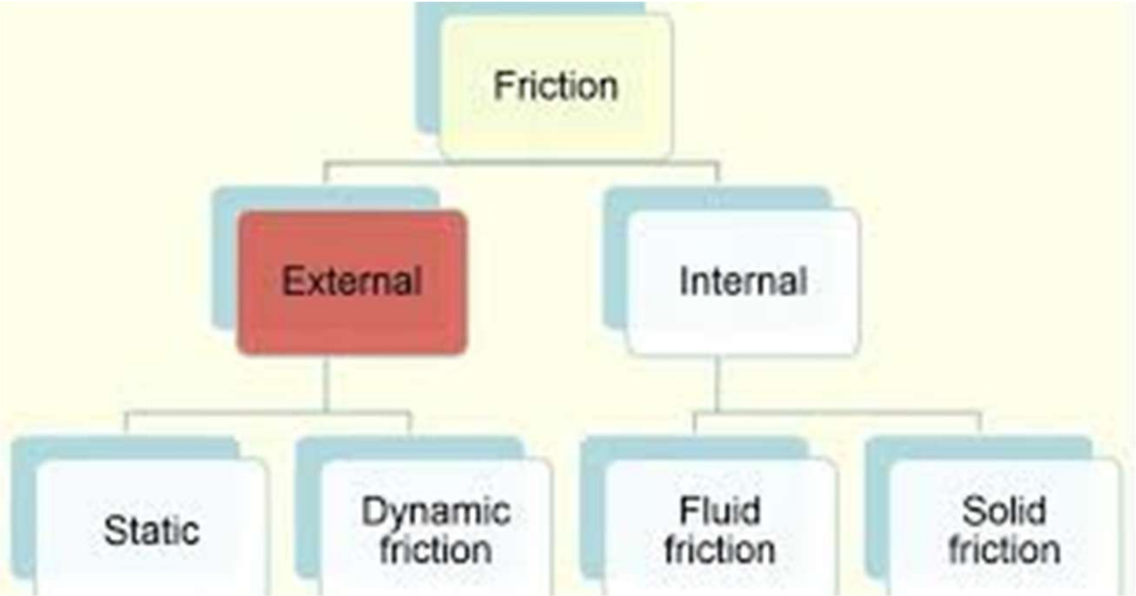
In this case, the object experiences resistance due to the fluid’s viscosity. This resistance is commonly referred to as **drag** in aerodynamics or hydrodynamics.

Dry and wet



- The dry friction is also known as solid body friction and it means that there is no coherent liquid or gas lubricant film between the two solid body surfaces.

Internal friction is a force that occurs within an object. It involves the maintenance of particles forming a material that remains in the same location in relation to one another.



Theories on Friction

- ***Leonardo da vinci(Earliest experimenter, 1452-1519) :***

As per Leonardo, “Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length”.

“Friction produces the double the amount of effort if weight be doubled”.

In other words, F α W.

Theories on Friction (Cont..)

- ***G. Amontons, 1699 :*** The friction force is independent of the nominal area (F ≠ A) of contact between two solid surfaces. The friction force is directly proportional F α N to the normal component of the load. He considered three cases (Fig.) and showed that friction force will vary as per the angle of application of load. As per Amontons μ = 0.3 for most of materials.

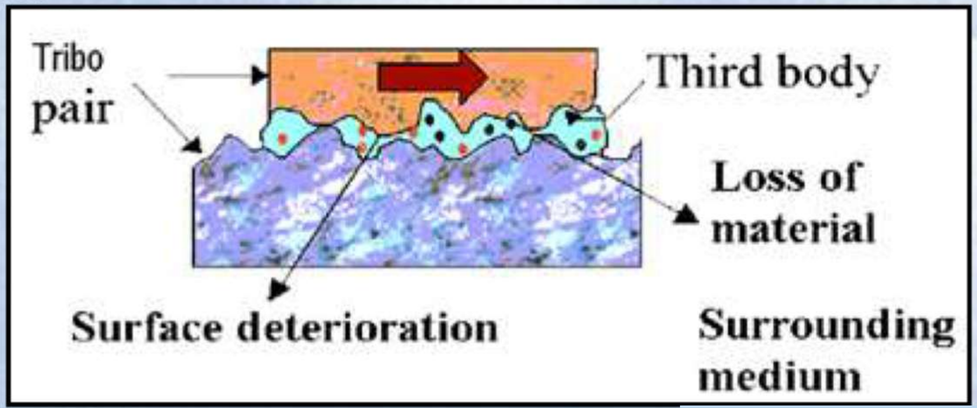


Fig. : Amonton`s work

Theories on Friction (Cont..)

❖ ***C.A. Coulomb 1781 (1736-1806) :***

✓ Clearly distinguished between static & kinetic frictions. Friction due to interlocking of rough surfaces.

Contact at discrete points μstatic ≥ μkinetic.

f ≠ func(A).

f ≠ func(v).

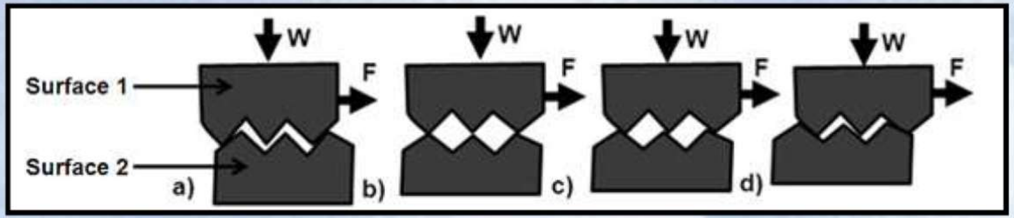
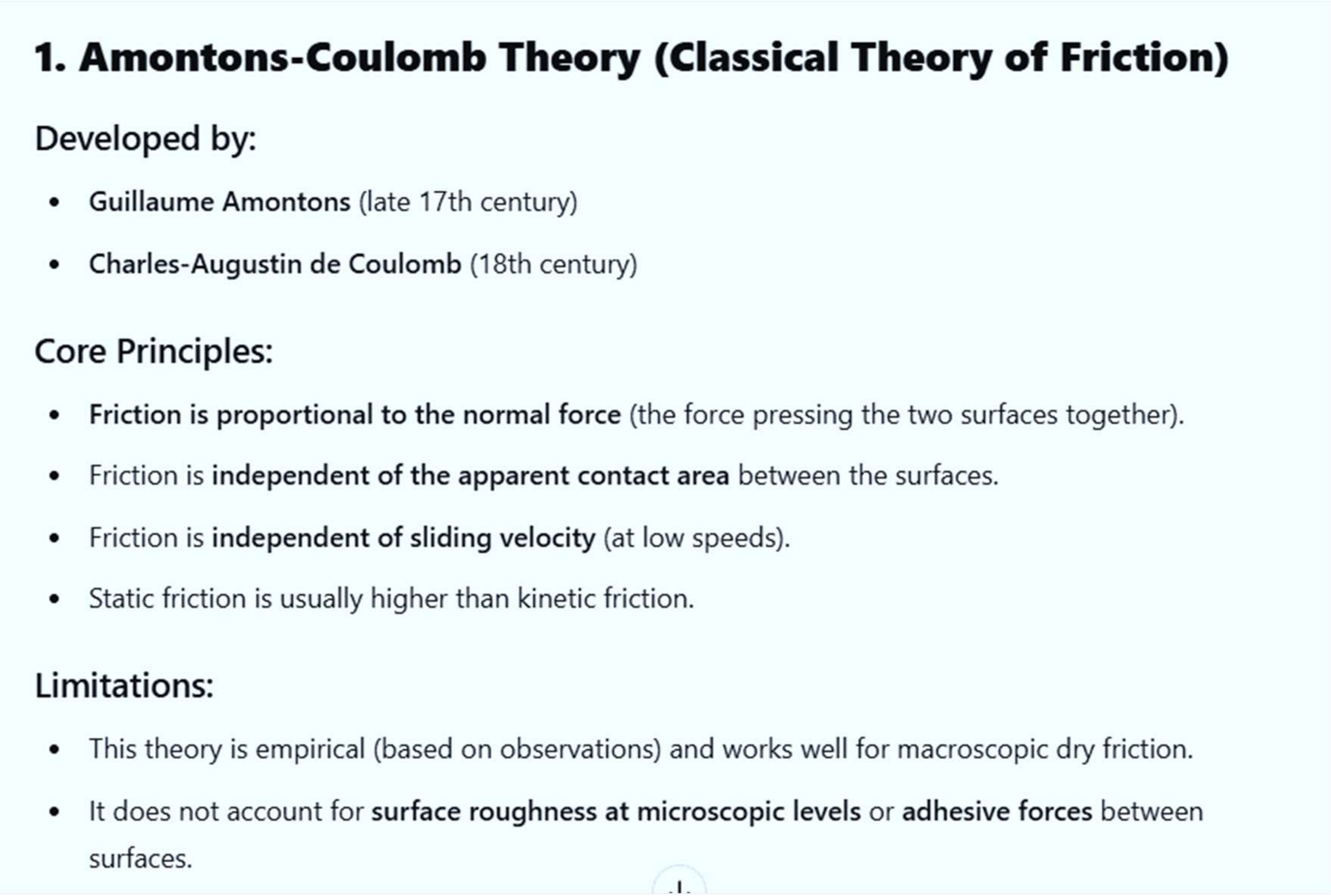


Fig. : Coulomb friction model.

✓ As per coulomb friction force is independent of sliding speed. But this law applies only approximately to dry surfaces for a reasonable low range of sliding speeds, which depends on heat dissipation capabilities of tribo-pairs.



1. Amontons-Coulomb Theory (Classical Theory of Friction)

Developed by:

- **Guillaume Amontons** (late 17th century)
- **Charles-Augustin de Coulomb** (18th century)

Core Principles:

- **Friction is proportional to the normal force** (the force pressing the two surfaces together).
- Friction is **independent of the apparent contact area** between the surfaces.
- Friction is **independent of sliding velocity** (at low speeds).
- Static friction is usually higher than kinetic friction.

Limitations:

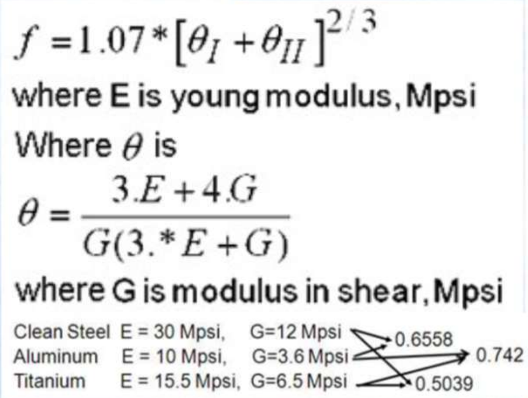
- This theory is empirical (based on observations) and works well for macroscopic dry friction.
- It does not account for **surface roughness at microscopic levels** or **adhesive forces** between surfaces.

Theories on Friction (Cont..)

- ***TOMLINSON's Theory of Molecular attraction, 1929 :***

  Tomlison based on experimental study provided relation between friction coefficient & elastic properties of material involved.

- As per Tomlison due to molecular attraction between metal, cold weld junctions are formed. Generally load on bearing surface is carried on just a few points. These are subjected to heavy unit pressure, and so probably weld together. Adhesion force developed at real area of contact.



$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

where E is young modulus, Mpsi

Where θ is

$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

Clean Steel E = 30 Mpsi, G=12 Mpsi
Aluminum E = 10 Mpsi, G=3.6 Mpsi
Titanium E = 15.5 Mpsi, G=6.5 Mpsi

Fig. : Examples on Tomlison formula.

- Fig. provides illustration related to Tomlison`s friction formula. This figure indicates f = 0.6558 for clean steel and aluminium, f = 0.742 for aluminium and titanium, and f = 0.5039 for clean steel and titanium.

Theories on Friction (Cont..)

- ***Scientific Explanation of Dry Friction :***
- There are two main friction sources: ***Adhesion and Deformation***. Force needed to plough asperities of harder surface through softer.
- In lubricated tribo-pair case, friction due to adhesion will be negligible, while for smoother surfaces under light load conditions deformation component of friction will be negligible.
- Fig. demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction.

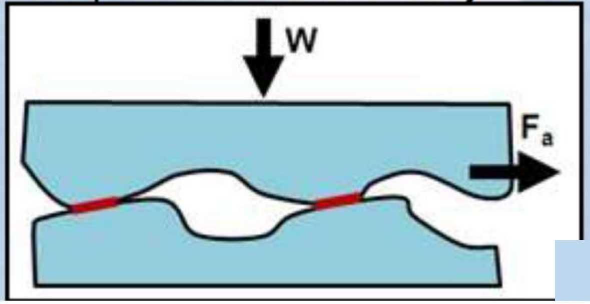


Fig. : Adhesion

Adhesion

- This theory is based on the fact that all surfaces are made of atoms.
- All atoms attract order one another by attractive force.
- For examples, if we press steel piece over indium piece (as shown in Fig.) they will bind across the region of contact.
- This process is sometimes called "cold welding," since the surfaces stick together strongly without the application of heat.

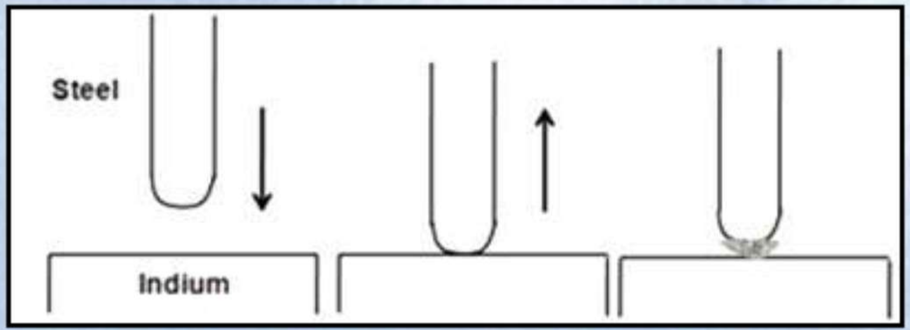
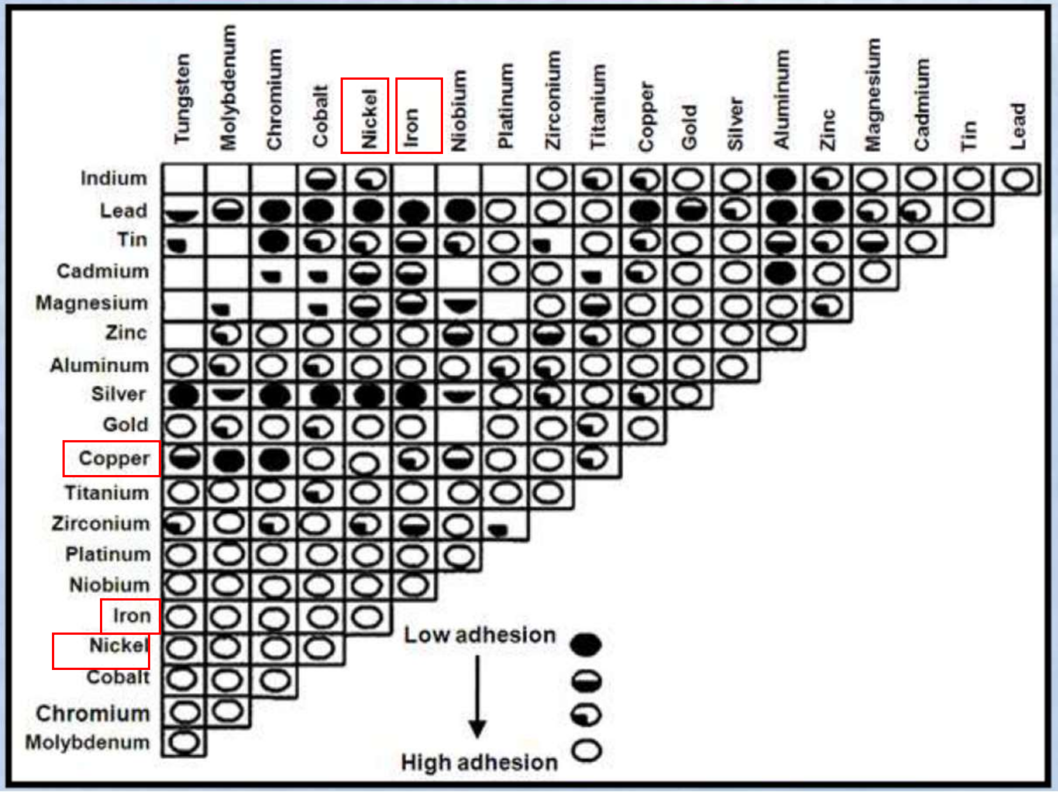


Fig. : Cold welding in steel and indium

Friction

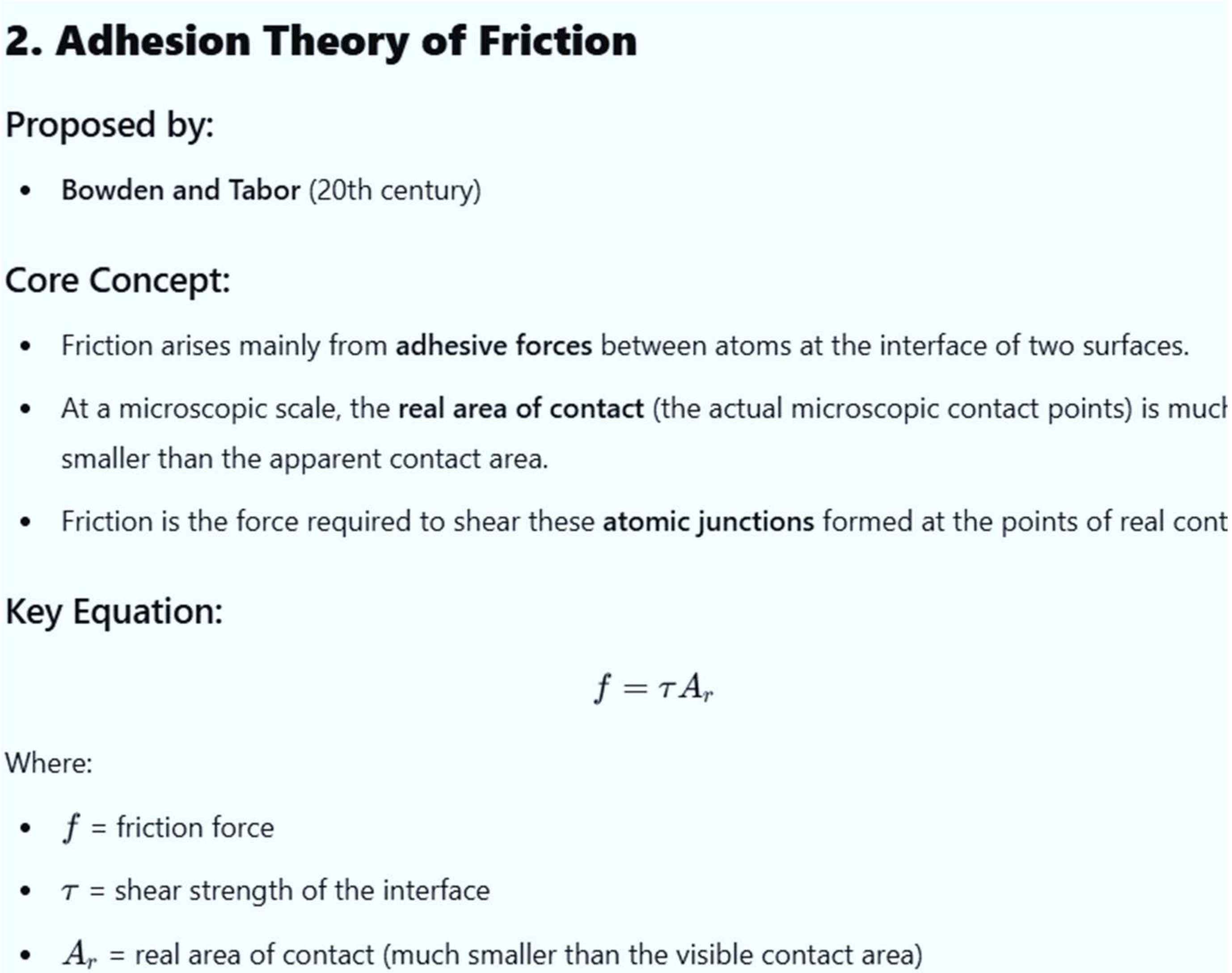
INTRODUCTION…..(Cont..)

- Generally, adhesion (ref. Fig.) increases the friction. So, while selecting metal pairs, low adhesion metal pairs must be selected to reduce friction force. Similar material pair must be avoided as similar materials have higher tendency of adhesion.



	Tungsten	Molybdenum	Chromium	Cobalt	Nickel	Iron	Niobium	Platinum	Zirconium	Titanium	Copper	Gold	Silver	Aluminum	Zinc	Magnesium	Cadmium	Tin	Lead
Indium				◒	◔				○	◔	◔	○	○	●	◔	○	○	○	○
Lead	◒	◒	●	●	●	●	●	○	○	○	●	◒	◔	●	●	◔	◔	○	
Tin	◔		●	◔	◔	◒	◔	○	◔	○	◔	○	○	◒	◔	◒	○		
Cadmium			◔	◔	◒	◒		○	○	◔	◔	○	○	●	○	○			
Magnesium		◔		◔	◒	◒	◒		○	◒	○	○	○	○	◔				
Zinc		◔	○	○	○	○	◒	○	◒	◔	○	○	○	○					
Aluminum	○	◔	○	◔	○	○	○	◔	◔	○	○	○	○						
Silver	●	◒	●	●	●	●	◒	○	◔	○	◔	○							
Gold	○	◔	○	◔	○	○		○	○	◔	○								
Copper	◒	●	●	○	○	◔	◒	○	○	◔									
Titanium	○	○	○	◔	○	○	○	○	○										
Zirconium	◔	○	◔	○	◔	◒	○	◔											
Platinum	○	○	○	○	○	○	○												
Niobium	○	○	○	○	○	○													
Iron	○	○	○	○	○														
Nickel	○	○	○	○															
Cobalt	○	○	○																
Chromium	○	○																	
Molybdenum	○																		

Low adhesion ●
↓ ◒
◔
High adhesion ○



2. Adhesion Theory of Friction

Proposed by:

- **Bowden and Tabor** (20th century)

Core Concept:

- Friction arises mainly from **adhesive forces** between atoms at the interface of two surfaces.
- At a microscopic scale, the **real area of contact** (the actual microscopic contact points) is much smaller than the apparent contact area.
- Friction is the force required to shear these **atomic junctions** formed at the points of real cont

Key Equation:

$$f = \tau A_r$$

Where:

- f = friction force
- τ = shear strength of the interface
- A_r = real area of contact (much smaller than the visible contact area)

THEORY OF ADHESIVE FRICTION (Cont..)

- Fig. shows the formulation and breakage of cold junctions. •
  - ✓ Two surfaces are pressed together under load W.
  - ✓ Material deforms until area of contact (A) is sufficient to support load W, A = W/H.
  - ✓ To move the surface sideway, it must overcome shear strength of junctions with force Fa.
  - ✓ $\mu = Fa/W = s/H$.
  - ✓ In other words shear strength(s) and hardness(H) of soft material decides the value of μ.
  - ✓ This means whatever properties of the other harder pairing material, μ would not change.

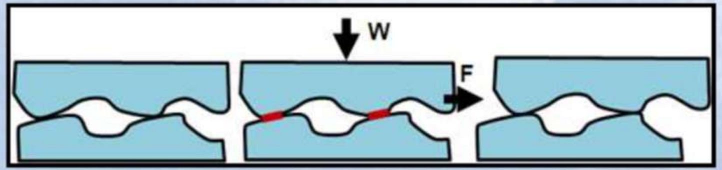
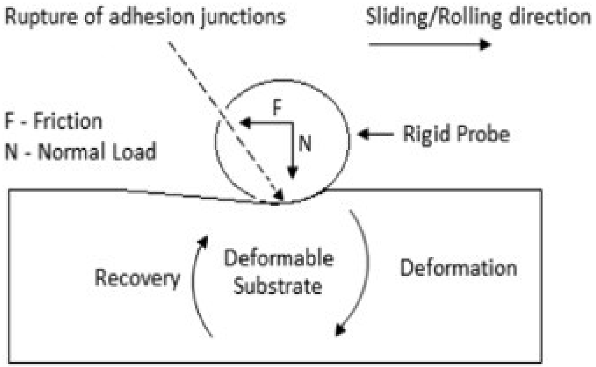


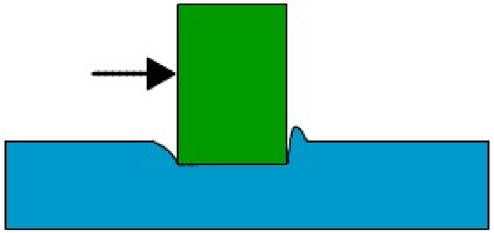
Fig. : Adhesion theory

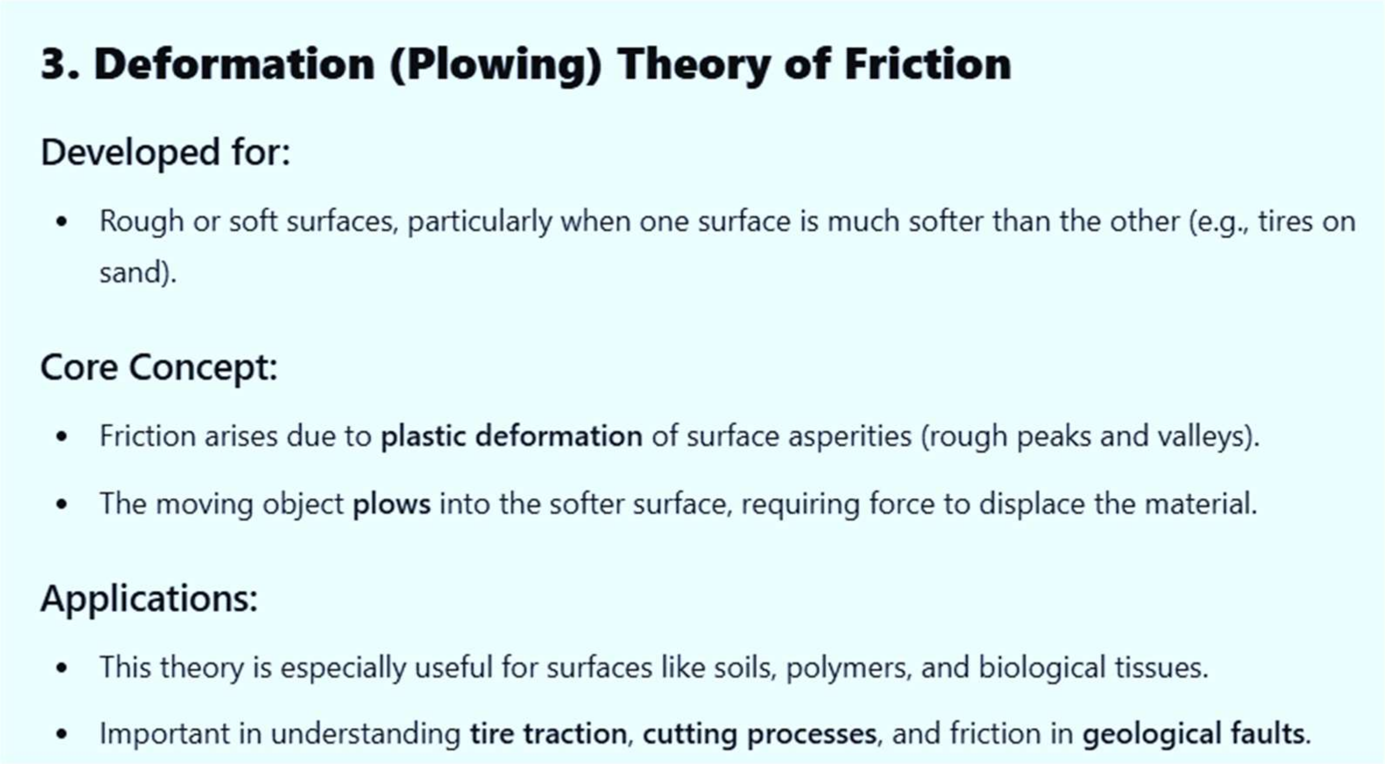
FRICTION DUE TO DEFORMATION

- Soft materials will deform when under pressure. This also increased the resistance to motion.

  surface touch the other.
- The slope of asperities governs the friction force.
- Sharp edges cause more friction compared to rounded edges.
- Expression for coefficient of friction can be derived based on the ploughing effect.
- Ploughing occurs when two bodies in contact have different hardness.
- The asperities on the harder surface may penetrate into the softer surface and produce grooves on it, if there is relative motion.







3. Deformation (Plowing) Theory of Friction

Developed for:

- Rough or soft surfaces, particularly when one surface is much softer than the other (e.g., tires on sand).

Core Concept:

- Friction arises due to **plastic deformation** of surface asperities (rough peaks and valleys).
- The moving object **plows** into the softer surface, requiring force to displace the material.

Applications:

- This theory is especially useful for surfaces like soils, polymers, and biological tissues.
- Important in understanding **tire traction**, **cutting processes**, and friction in **geological faults**.

FRICTION DUE TO DEFORMATION (Cont..)

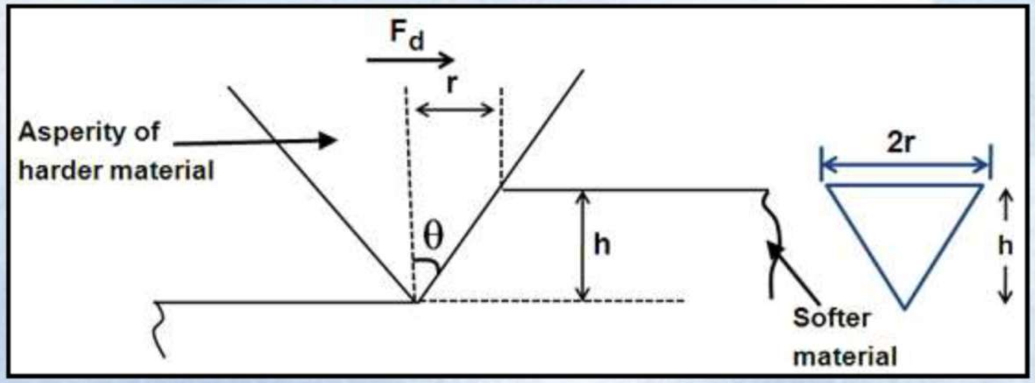


Fig. : Deformation theory[1].

- Contact between tribo-pairs only occurs at discrete points. Assume n conical asperities of hard metal in contact with flat soft metal, vertically project area of contact.

$$W = n(0.5 * \pi r^2)H$$

$$A = n\left(0.5 * \pi r^2\right)$$

$$F = n(rh)H$$

[1]. J Halling, Principles of Tribology, The Macmillan Press Ltd, London, 1975.

FRICTION DUE TO DEFORMATION (Cont..)

- μd = (F/W), substituting the equations of F and W, we get μd = (2/π)cot θ : This relation shows important of cone angle, θ.
- Table lists the μd for various θ values.
- In practice slopes of real surfaces are lesser than 100 (i.e. θ > 800), therefore μd = 0.1. If we add this value(μd = 0.1), total μ, should not exceed 0.3. Total μ, representing contribution for both ploughing and adhesion terms.

Table

θ	μ
5	7.271
10	3.608
20	1.748
30	1.102
40	0.758
50	0.534
60	0.367
70	0.231
80	0.112
85	0.055

PLOUGHING BY SPHERICAL ASPERITY

- If we consider asperities on solid surfaces are spherical, vertical projected area of contact:

$$A = n\left(0.5 * \pi r^2\right)$$

$$or\ A = n\left(0.5 * \pi (0.5\ d)^2\right)$$

$$or\ A = n\ \frac{\pi\ d^2}{8}$$

$$W = n \frac{\pi\ d^2}{8} H$$

$$F = n\ \frac{2\,h\,d}{3} H$$

$$\mu_d = \frac{2\,h\,d\,8}{3\pi d^2} = \frac{16}{3\pi}\frac{h}{d} = \frac{16}{3\pi}\frac{h}{\sqrt{8\,h\,R}} = 0.6\sqrt{\frac{h}{R}}$$

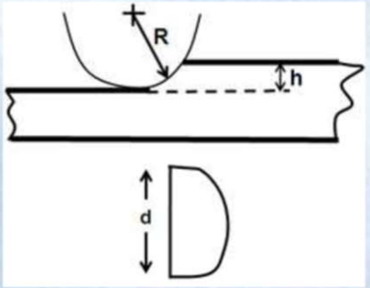
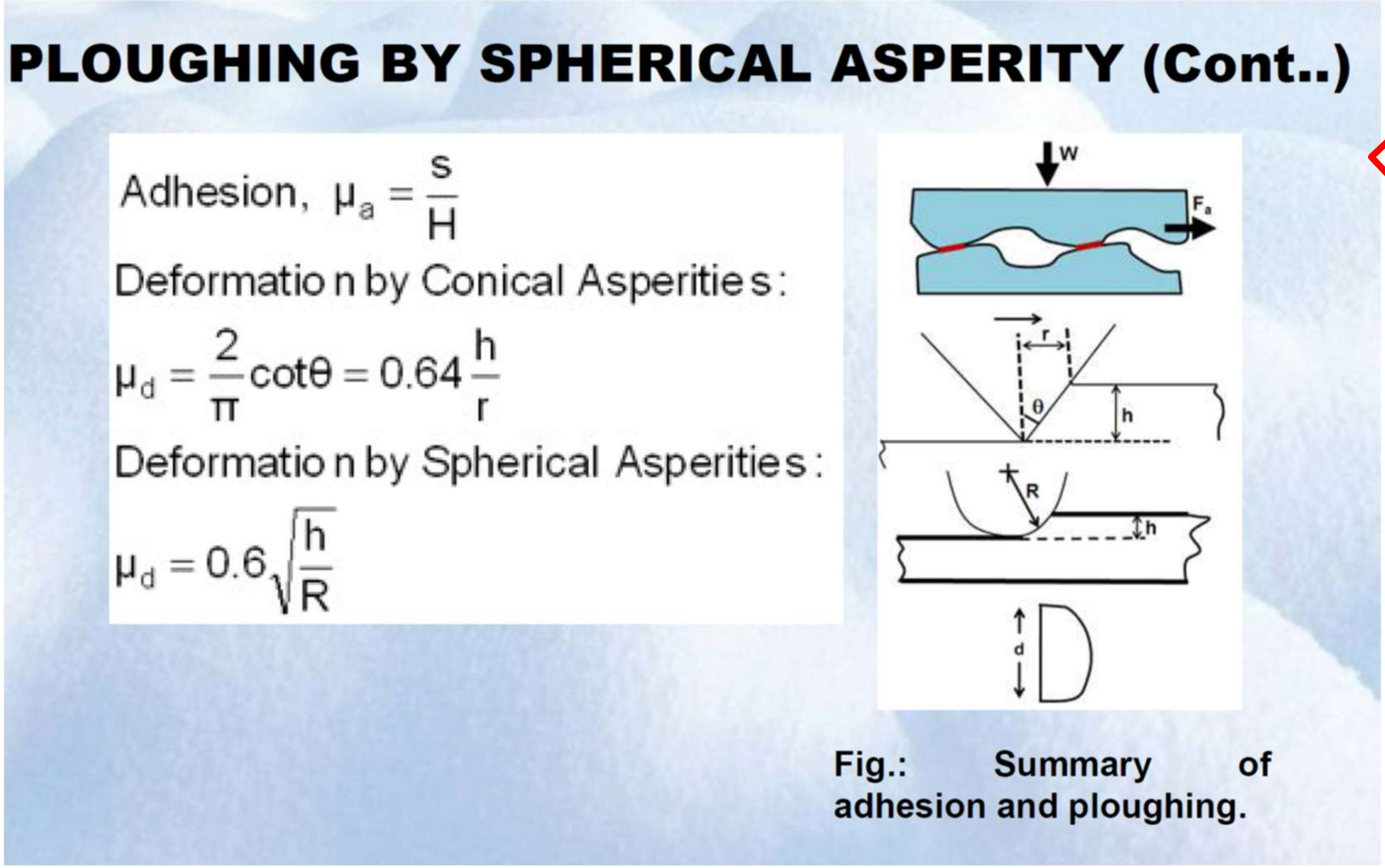


Fig. : Spherical asperity.

- Generally h << R, therefore μd Ξ 0.1. This means total μ, should not exceed 0.3. Summary of theories related to adhesion and ploughing effects.



PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Adhesion, $\mu_a = \frac{s}{H}$

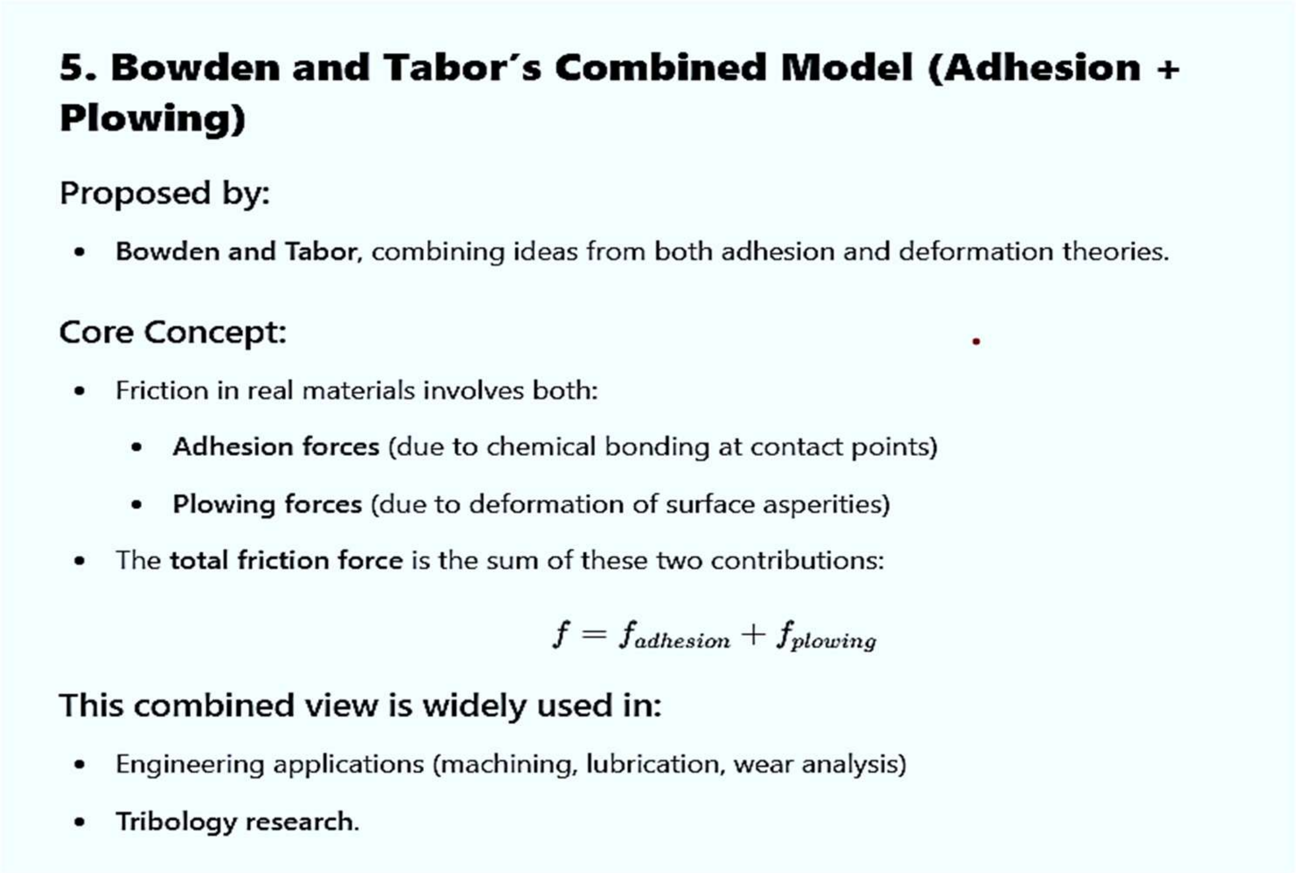
Deformation by Conical Asperities:

$$\mu_d = \frac{2}{\pi}\cot\theta = 0.64\frac{h}{r}$$

Deformation by Spherical Asperities:

$$\mu_d = 0.6\sqrt{\frac{h}{R}}$$

Fig.: Summary of adhesion and ploughing.



5. Bowden and Tabor's Combined Model (Adhesion + Plowing)

Proposed by:

- **Bowden and Tabor**, combining ideas from both adhesion and deformation theories.

Core Concept:

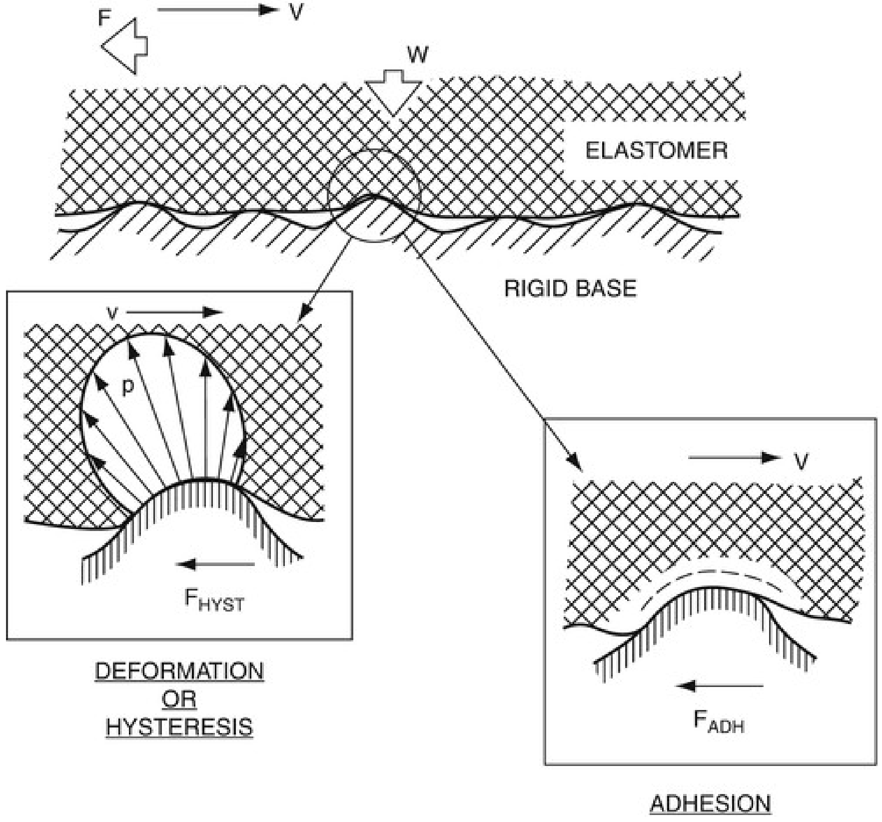
- Friction in real materials involves both:
  - **Adhesion forces** (due to chemical bonding at contact points)
  - **Plowing forces** (due to deformation of surface asperities)
- The **total friction force** is the sum of these two contributions:

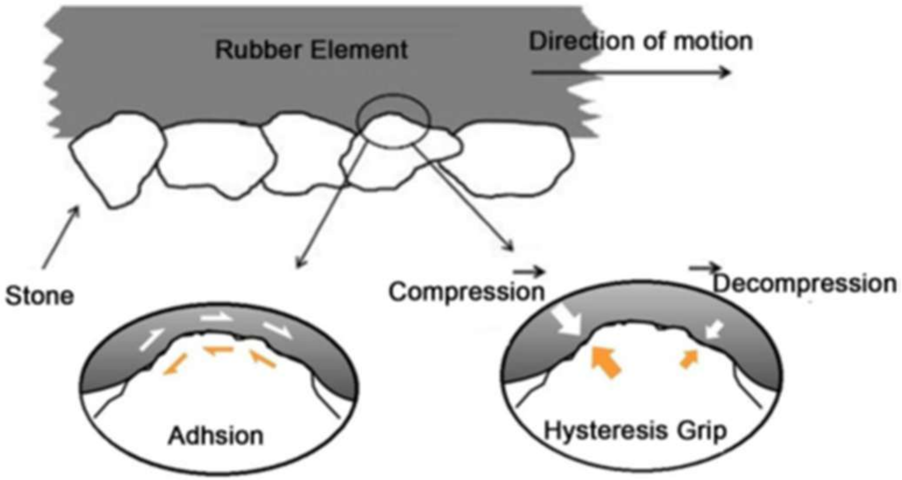
$$f = f_{adhesion} + f_{plowing}$$

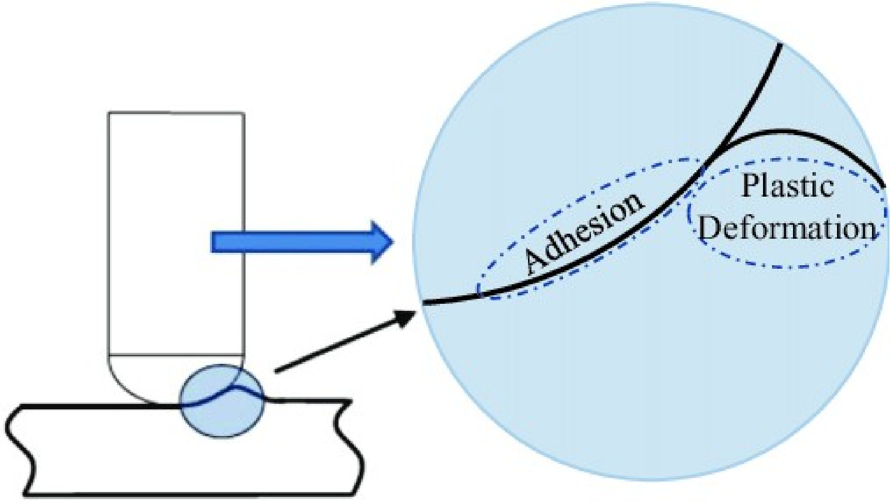
This combined view is widely used in:

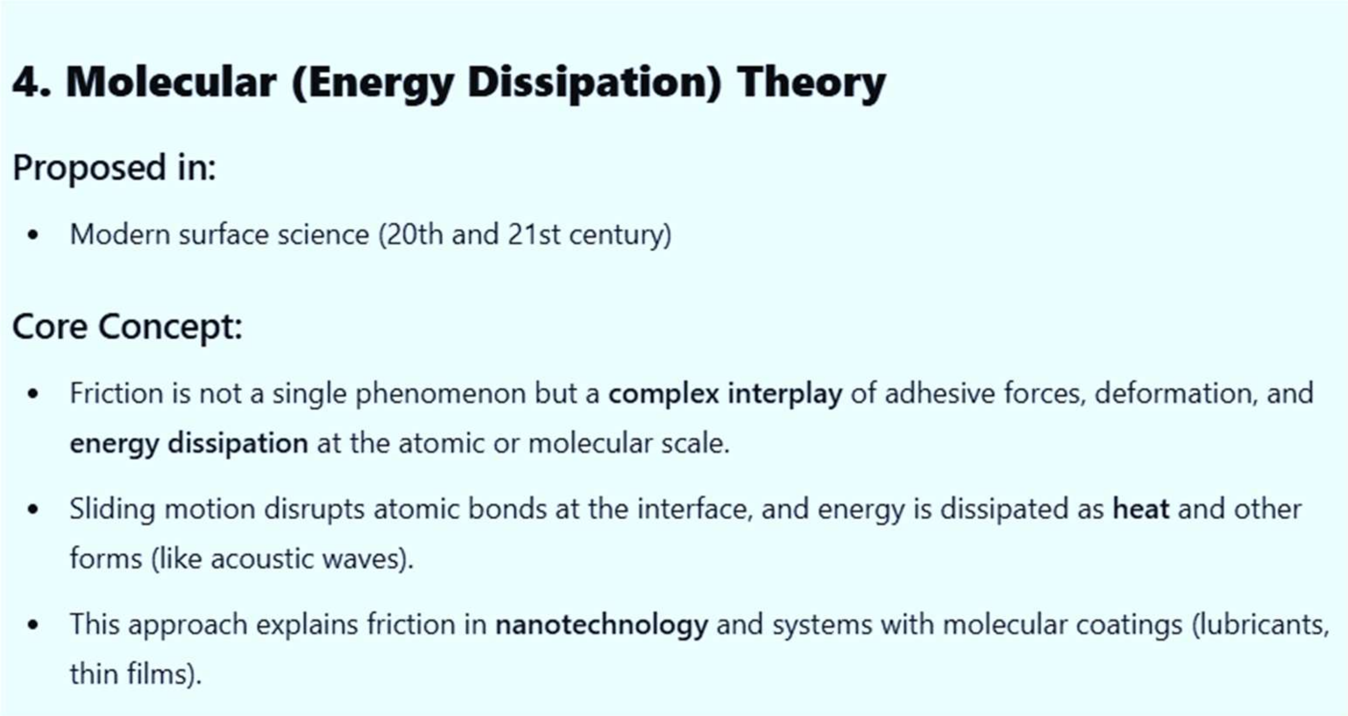
- Engineering applications (machining, lubrication, wear analysis)
- **Tribology research.**

Adhesion and deformation









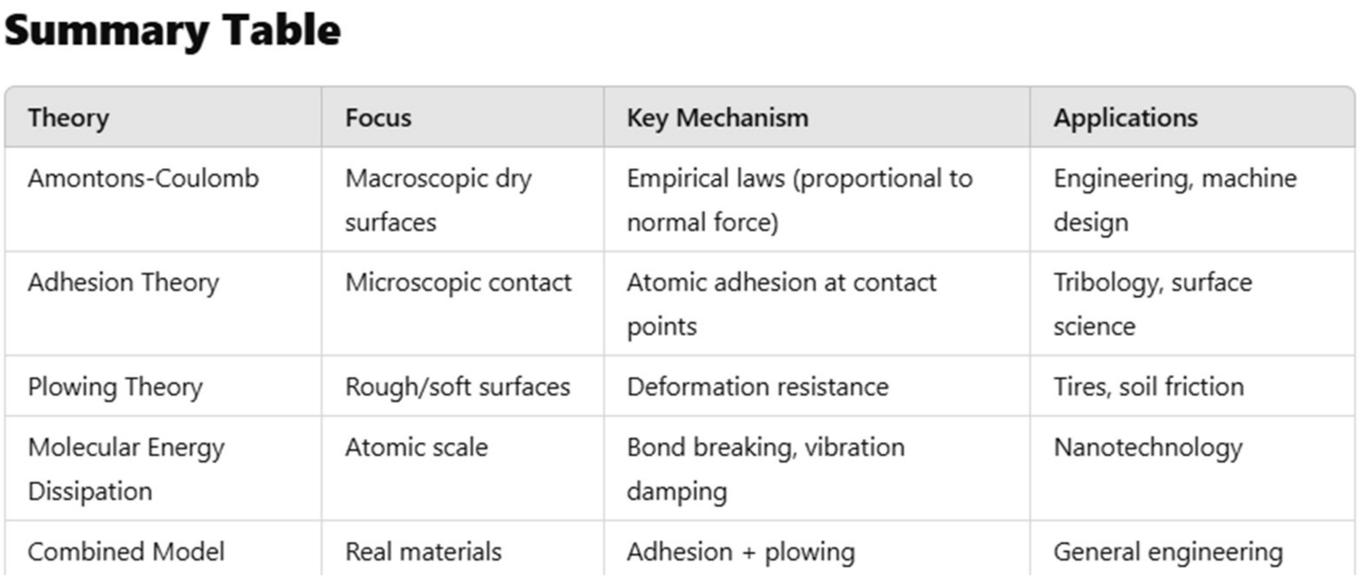
4. Molecular (Energy Dissipation) Theory

Proposed in:

- Modern surface science (20th and 21st century)

Core Concept:

- Friction is not a single phenomenon but a **complex interplay** of adhesive forces, deformation, and **energy dissipation** at the atomic or molecular scale.
- Sliding motion disrupts atomic bonds at the interface, and energy is dissipated as **heat** and other forms (like acoustic waves).
- This approach explains friction in **nanotechnology** and systems with molecular coatings (lubricants, thin films).



Summary Table

Theory	Focus	Key Mechanism	Applications
Amontons-Coulomb	Macroscopic dry surfaces	Empirical laws (proportional to normal force)	Engineering, machine design
Adhesion Theory	Microscopic contact	Atomic adhesion at contact points	Tribology, surface science
Plowing Theory	Rough/soft surfaces	Deformation resistance	Tires, soil friction
Molecular Energy Dissipation	Atomic scale	Bond breaking, vibration damping	Nanotechnology
Combined Model	Real materials	Adhesion + plowing	General engineering

How do we measure friction?

Macroscale Friction Test

Friction tester under constant normal load
Geometrically constrained system

Microscale and Nanoscale Friction Test

Atomic force microscope (AFM)
Scanning probe microscope (SPM)
etc.

Friction at Nano- and Micro-scale Contacts

Macroscale
  - >100 µm
  - µ ~ 0.4 to 0.7
  - Plastic deformation

- Microscale
  - ~ 10 µm
  - µ ~ 0.7 to 1
  - Surface energy, meniscus, and adhesion at the interface

- Nanoscale contacts
  - ~ 10 nm
  - Interatomic forces
  - µ ~ 0.07 (MD simulation results)

Measurement of Friction

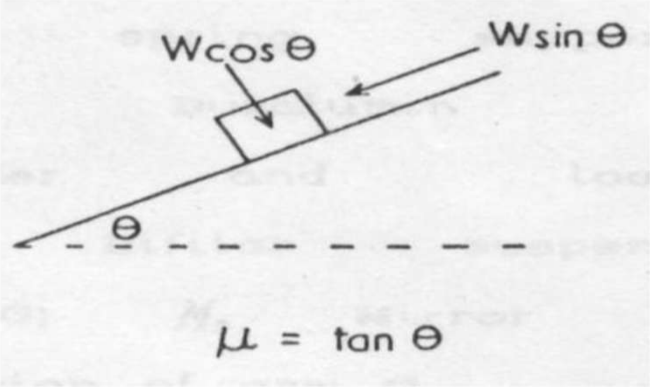
- To measure the friction, the basic requirements are simply a means of applying a normal load W and a means of measuring a tangential force F.

- Method -1:

  If the lower surface is flat, the simplest method is to use the gravity loading and to tilt the lower surface until sliding begins

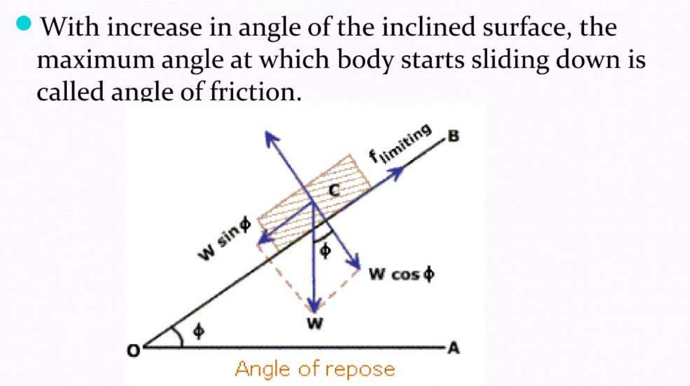
  If θ is the angle at which sliding begins, then, normal force = w cos θ, and tangential force = w sinθ,

  so that, μ = tan θ.



Inclined Plane Test (Simple Method)

- Place one material on a sloped surface of the other material.
- Slowly increase angle until sliding begins.

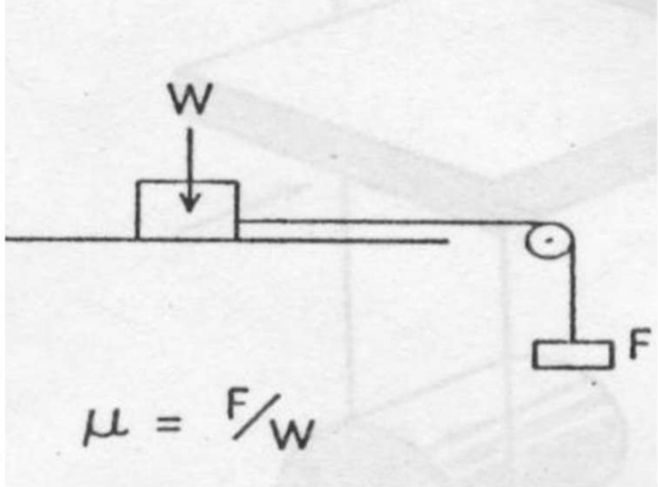


- With increase in angle of the inclined surface, the maximum angle at which body starts sliding down is called angle of friction.

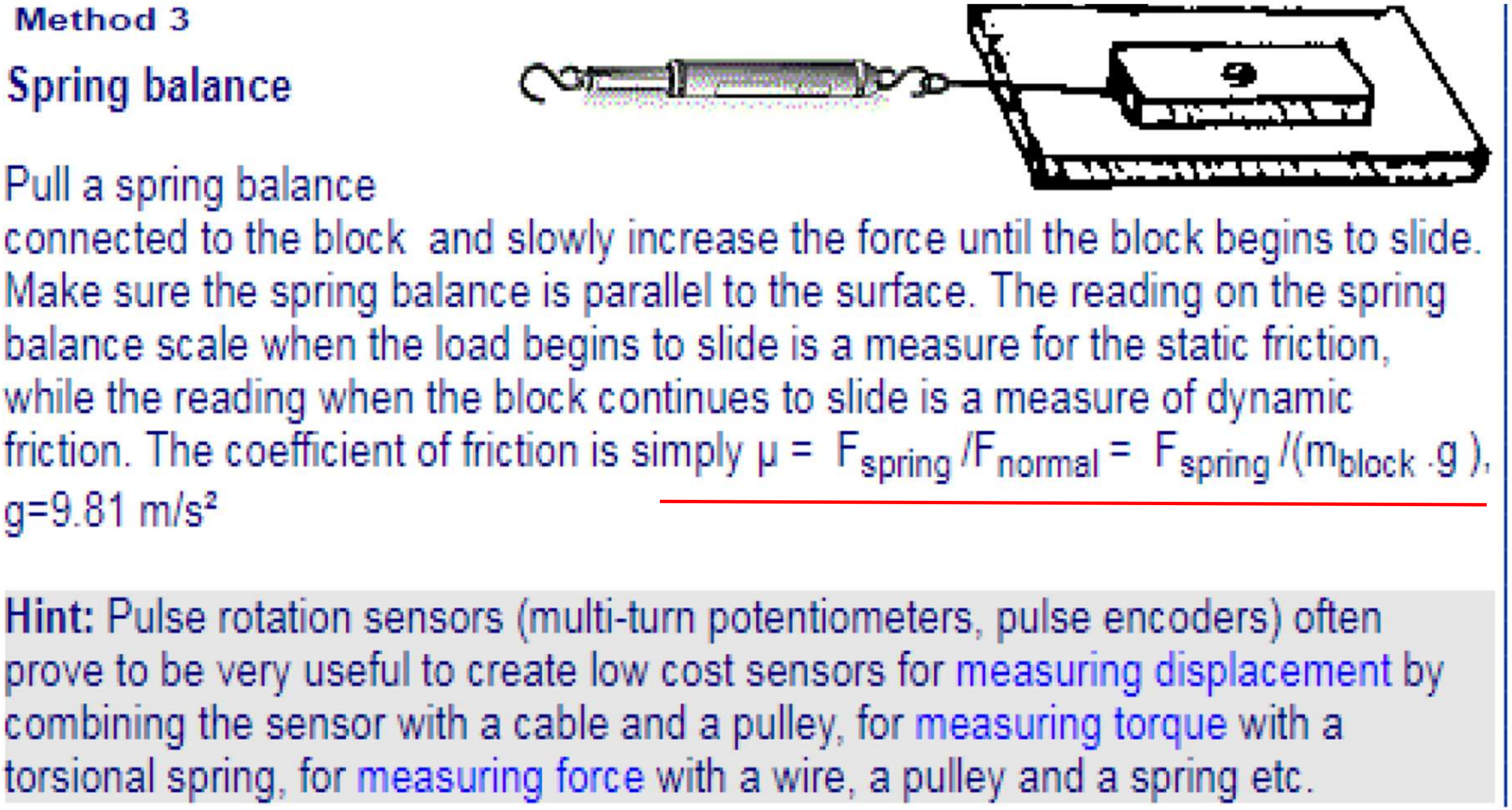
Angle of repose

- It is a convenient quick rough method to determine μ, but the vibration during the tilting may produce error.
- Generally, once sliding is started at an angle θ, the upper body accelerates down the slope.
- This is because the friction to start sliding (the static coefficient of friction μs) is generally greater than the friction which arises during sliding (the coefficient of kinetic friction μk).

- The second method also uses the gravity loading but the lower surface is kept horizontal and the tangential loading is applied by means of dead load over pulley and μ = F/W.



- Both the methods are however, defective because of the inertia of the moving parts they cannot readily detect fluctuations which occur during sliding. For this reason, it is often more fruitful to use a device of high natural frequency. On the basis of this approach various sophisticated apparatus have been developed.



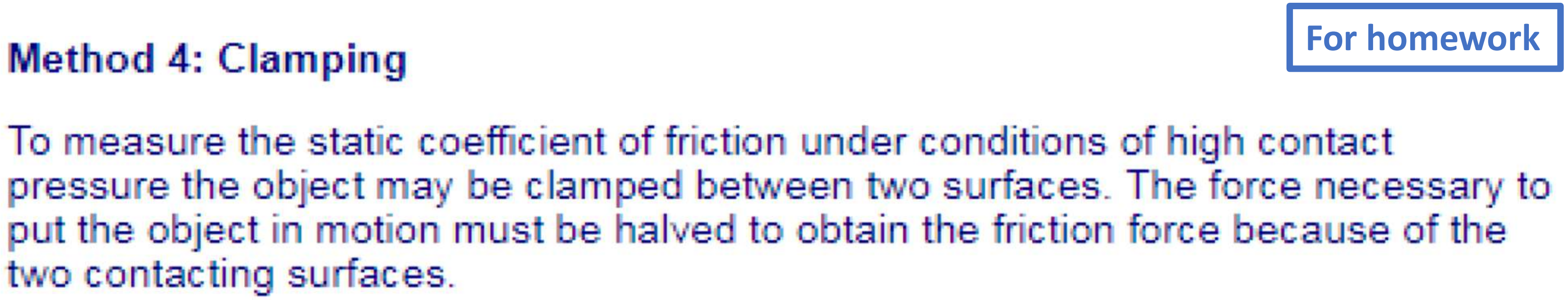
Method 3

Spring balance

Pull a spring balance connected to the block and slowly increase the force until the block begins to slide. Make sure the spring balance is parallel to the surface. The reading on the spring balance scale when the load begins to slide is a measure for the static friction, while the reading when the block continues to slide is a measure of dynamic friction. The coefficient of friction is simply $\mu = F_{spring} / F_{normal} = F_{spring} / (m_{block} \cdot g)$, $g = 9.81 \text{ m/s}^2$

Hint: Pulse rotation sensors (multi-turn potentiometers, pulse encoders) often prove to be very useful to create low cost sensors for measuring displacement by combining the sensor with a cable and a pulley, for measuring torque with a torsional spring, for measuring force with a wire, a pulley and a spring etc.

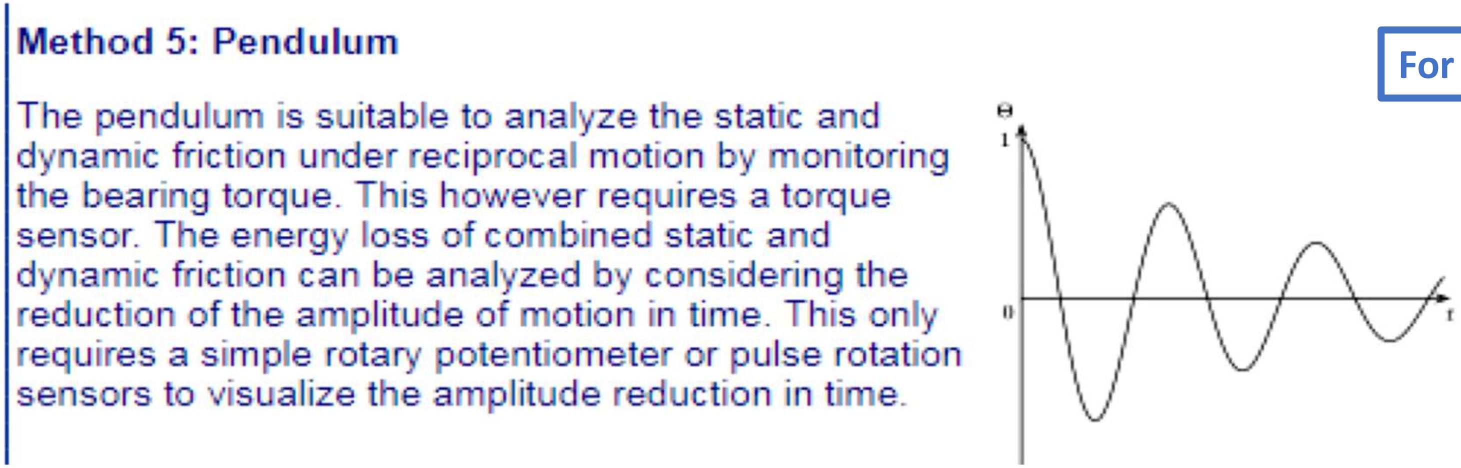
For homework



Method 4: Clamping

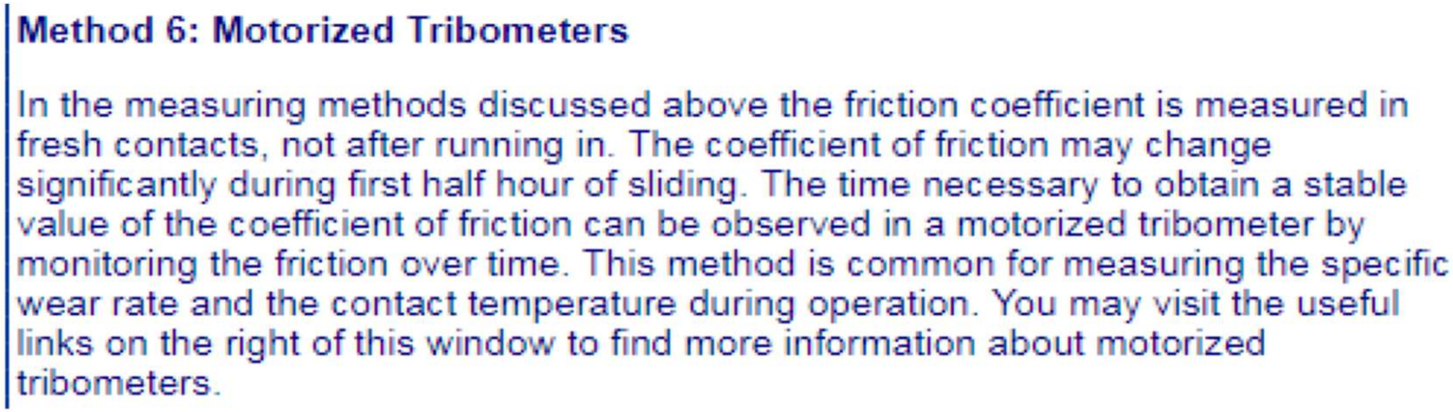
To measure the static coefficient of friction under conditions of high contact pressure the object may be clamped between two surfaces. The force necessary to put the object in motion must be halved to obtain the friction force because of the two contacting surfaces.

For homework



Method 5: Pendulum

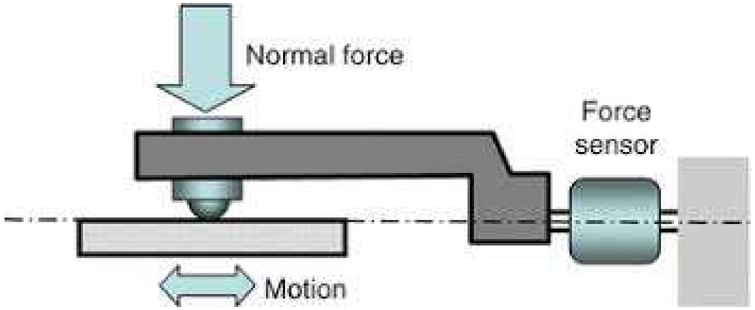
The pendulum is suitable to analyze the static and dynamic friction under reciprocal motion by monitoring the bearing torque. This however requires a torque sensor. The energy loss of combined static and dynamic friction can be analyzed by considering the reduction of the amplitude of motion in time. This only requires a simple rotary potentiometer or pulse rotation sensors to visualize the amplitude reduction in time.



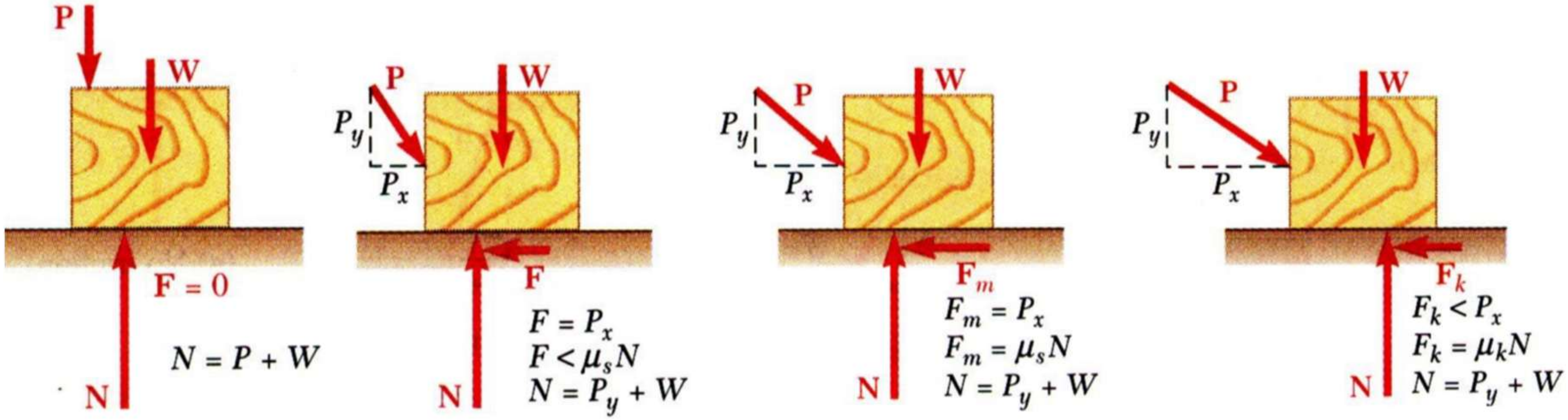
Method 6: Motorized Tribometers

In the measuring methods discussed above the friction coefficient is measured in fresh contacts, not after running in. The coefficient of friction may change significantly during first half hour of sliding. The time necessary to obtain a stable value of the coefficient of friction can be observed in a motorized tribometer by monitoring the friction over time. This method is common for measuring the specific wear rate and the contact temperature during operation. You may visit the useful links on the right of this window to find more information about motorized tribometers.

These devices continuously monitor friction force under controlled loads, speeds, and environments (can even simulate seawater immersion)



- Four situations can occur when a rigid body is in contact with a horizontal surface:



- No friction, ($P_x = 0$)
- No motion, ($P_x < F$)
- Motion impending, ($P_x = F_m$)
- Motion, ($P_x > F_m$)

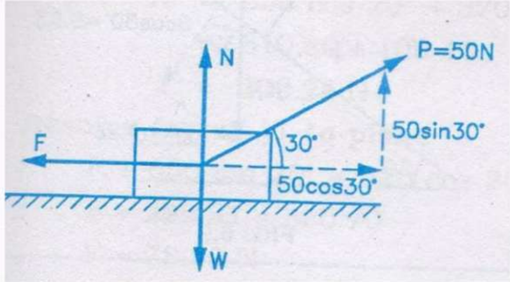
-:EXAMPLE:-

A Pull of 50 N inclined at 30° to the horizontal is necessary to move a wooden block on horizontal table. If coefficient of friction is 0.20, find the weight of wooden block.

Solution :

P = 50 N

$\mu = 0.20$



Resolve | | to plane :

F = 50 cos 30°

F = 43.30 N

μ = F/N

0.20 = 43.30/N

N = 216.5

Resolve (perpendicular) to plane

N + 50 sin 30° = W

216.5 + 25 = W

W = 241.5 N

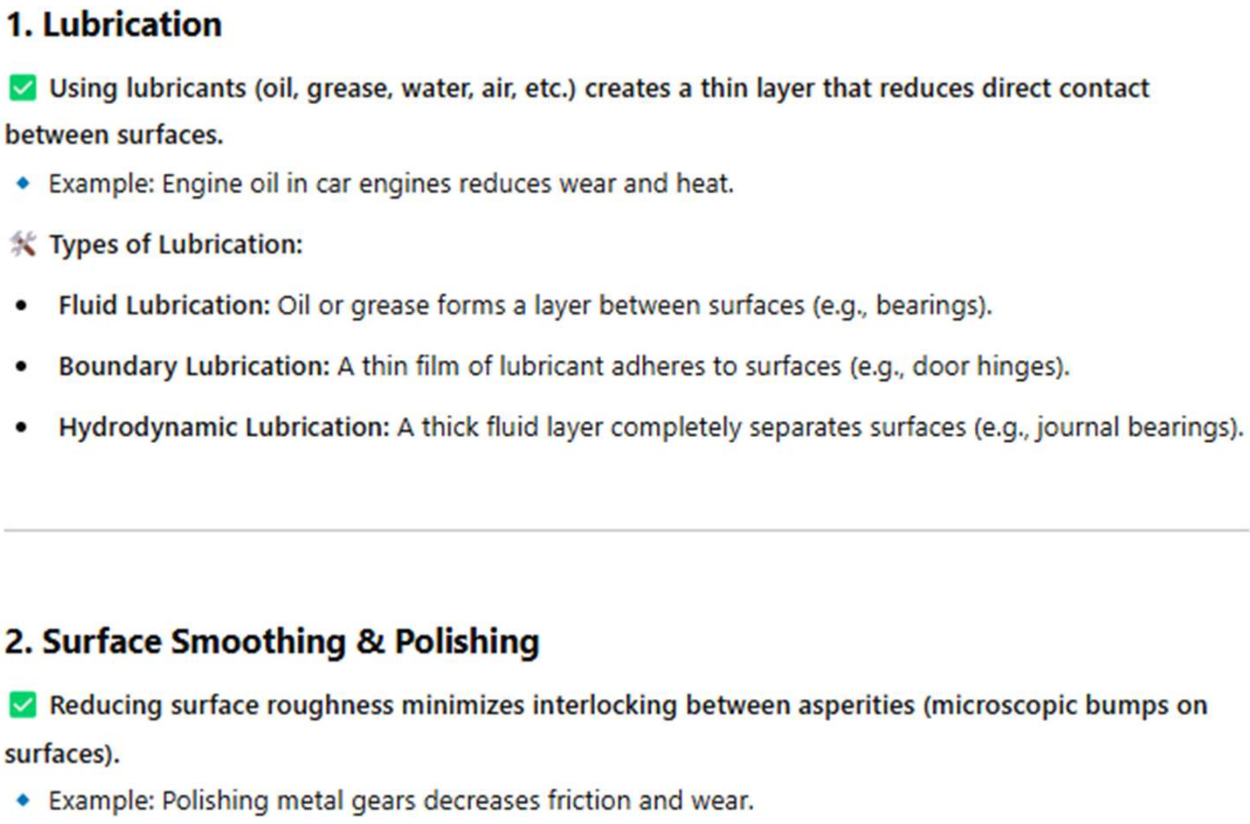
2. **Friction Mechanisms**

    - **Adhesion Theory**: Friction arises due to microscopic bonding between contacting surfaces.
    - **Deformation (Plowing) Theory**: Friction is influenced by surface roughness and material deformation.
    - **Third-Body Friction**: The presence of particles or lubricants affects frictional behavior.

Friction is affected by the following:

1. Presence of wear particles and externally introduced particles at the sliding interface
2. Relative hardness of the materials in contact
3. Externally applied load and/or displacement
4. Environmental conditions such as temperature and lubricants
5. Surface topography
6. Microstructure or morphology of materials

How to Decrease Friction: Strategies & Methods



1. Lubrication

✅ **Using lubricants (oil, grease, water, air, etc.) creates a thin layer that reduces direct contact between surfaces.**

◆ Example: Engine oil in car engines reduces wear and heat.

🛠️ **Types of Lubrication:**

- **Fluid Lubrication:** Oil or grease forms a layer between surfaces (e.g., bearings).
- **Boundary Lubrication:** A thin film of lubricant adheres to surfaces (e.g., door hinges).
- **Hydrodynamic Lubrication:** A thick fluid layer completely separates surfaces (e.g., journal bearings).

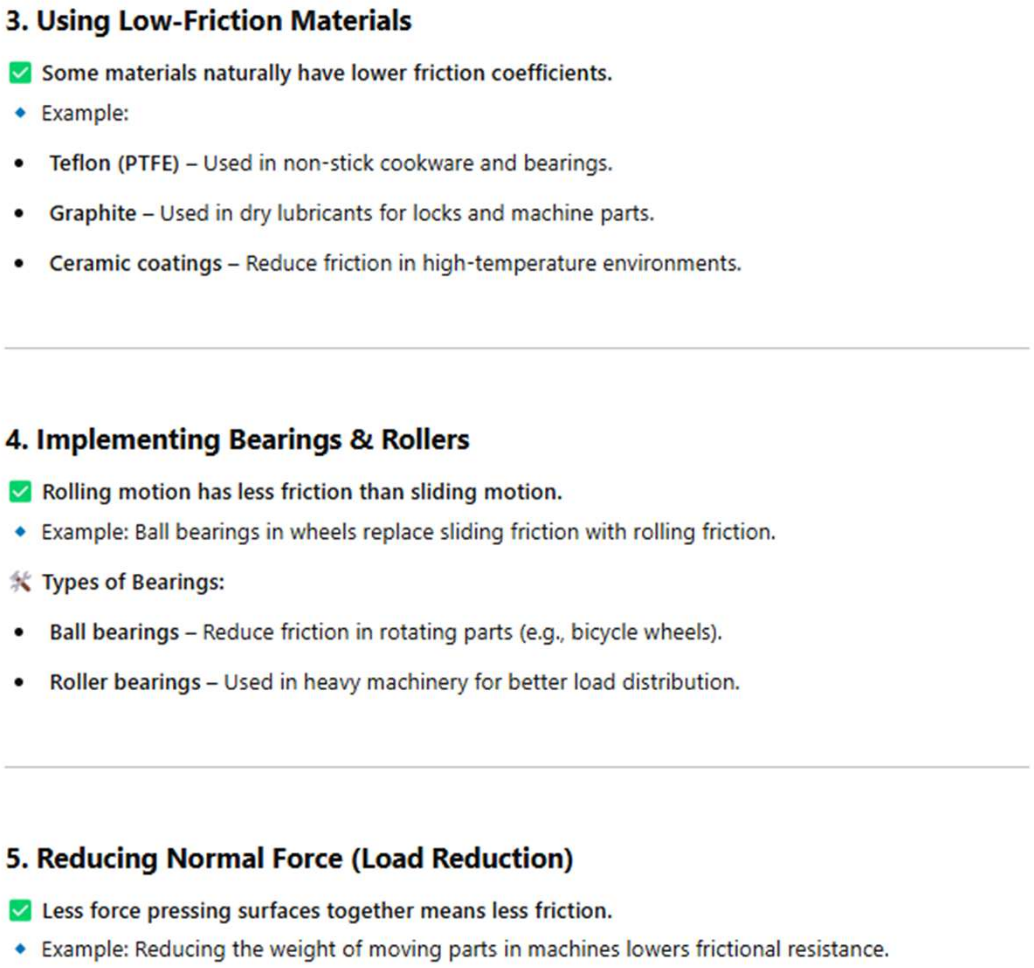
---

2. Surface Smoothing & Polishing

✅ **Reducing surface roughness minimizes interlocking between asperities (microscopic bumps on surfaces).**

◆ Example: Polishing metal gears decreases friction and wear.

How to Decrease Friction: Strategies & Methods



3. Using Low-Friction Materials

✅ **Some materials naturally have lower friction coefficients.**

🔹 Example:

- **Teflon (PTFE)** – Used in non-stick cookware and bearings.
- **Graphite** – Used in dry lubricants for locks and machine parts.
- **Ceramic coatings** – Reduce friction in high-temperature environments.

---

4. Implementing Bearings & Rollers

✅ **Rolling motion has less friction than sliding motion.**

🔹 Example: Ball bearings in wheels replace sliding friction with rolling friction.

🛠 **Types of Bearings:**

- **Ball bearings** – Reduce friction in rotating parts (e.g., bicycle wheels).
- **Roller bearings** – Used in heavy machinery for better load distribution.

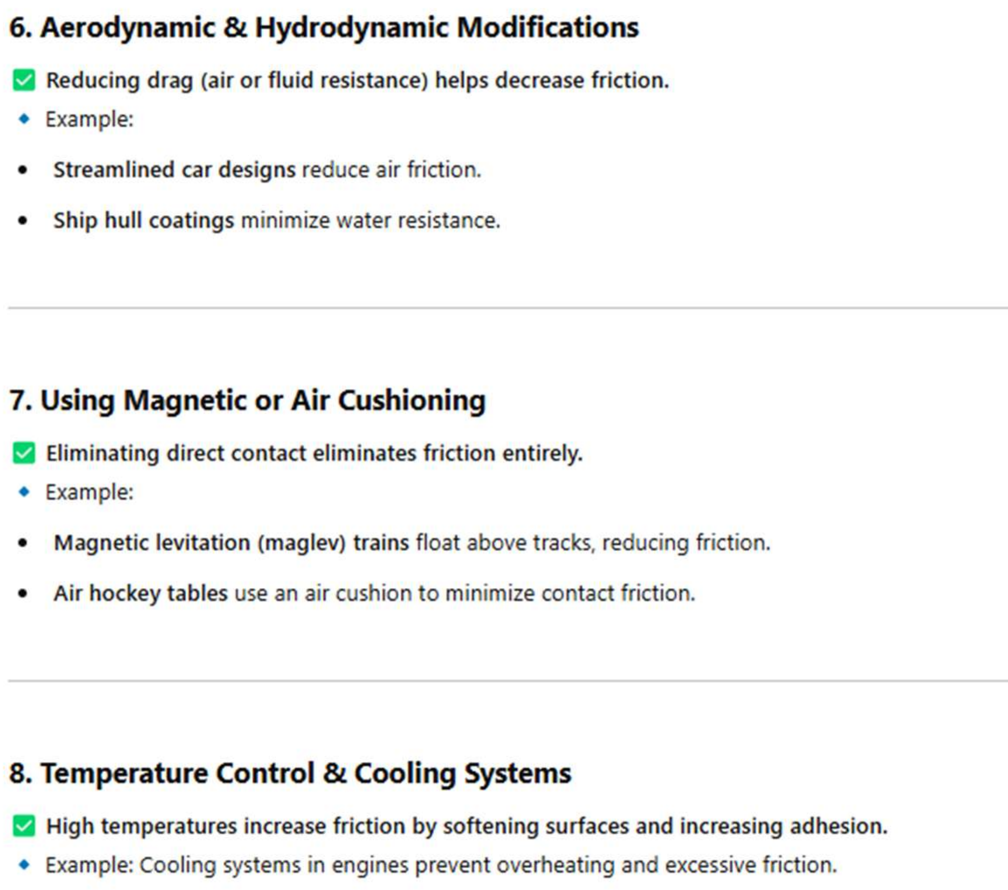
---

5. Reducing Normal Force (Load Reduction)

✅ **Less force pressing surfaces together means less friction.**

🔹 Example: Reducing the weight of moving parts in machines lowers frictional resistance.

How to Decrease Friction: Strategies & Methods



6. Aerodynamic & Hydrodynamic Modifications

☑ **Reducing drag (air or fluid resistance) helps decrease friction.**

◆ Example:

- **Streamlined car designs** reduce air friction.
- **Ship hull coatings** minimize water resistance.

---

7. Using Magnetic or Air Cushioning

☑ **Eliminating direct contact eliminates friction entirely.**

◆ Example:

- **Magnetic levitation (maglev) trains** float above tracks, reducing friction.
- **Air hockey tables** use an air cushion to minimize contact friction.

---

8. Temperature Control & Cooling Systems

☑ **High temperatures increase friction by softening surfaces and increasing adhesion.**

◆ Example: Cooling systems in engines prevent overheating and excessive friction.

Streamlined shape of a car and a aeroplane .

Wear

Some of the Basic Questions

What is wear?

What is wear type?

What is the wear mechanism?

How do we measure the wear rate?

How should we reduce the wear rate of materials?

What factors would affect the wear rate?

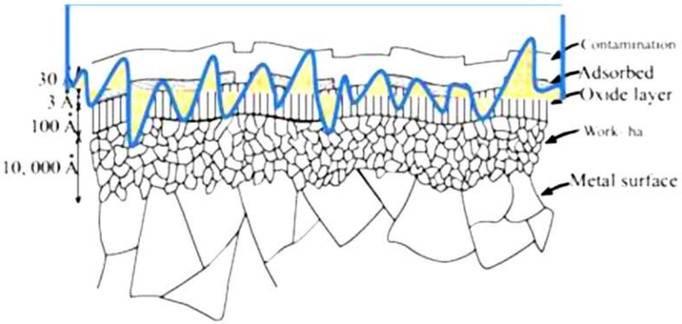
How can wear be prevented?

Wear

- Loss of material by the passage of hard particles over a surface

Wear can be defined as the damage or removal of material that a solid **surface** has undergone due to sliding, rolling, and impact against another solid surface.

Wear is the **damaging**, **gradual removal** or **deformation** of material at solid surfaces.
Causes of wear can be mechanical (e.g., erosion) or chemical (e.g., corrosion).



Wear

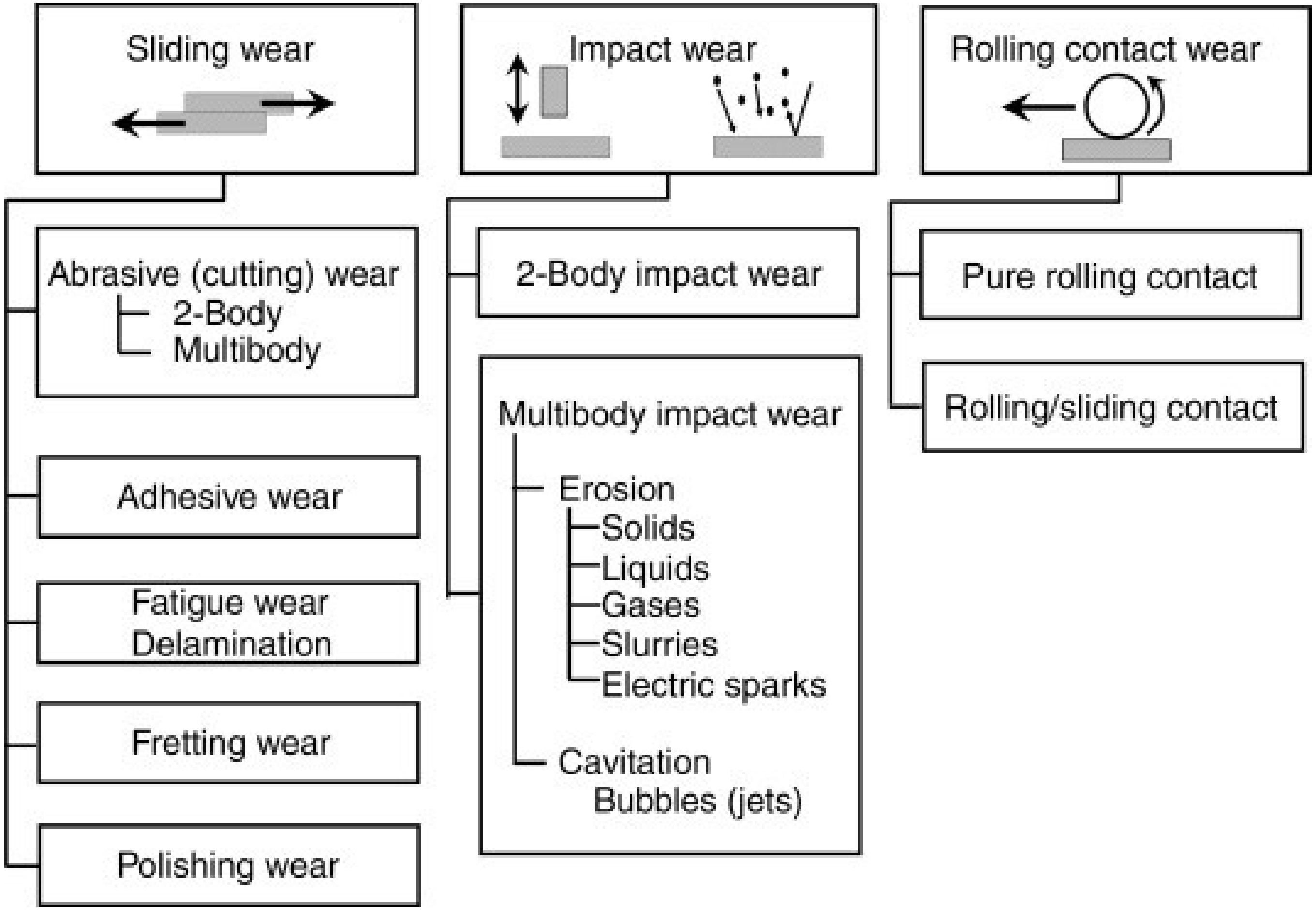
It is not a material property, but rather a system response.

Typically, wear is **undesirable** as it can lead to increased friction, and ultimately to material failure or loss of functionality.

This phenomenon typically occurs over time and can be influenced by a range of factors including load, relative motion, material properties, surface roughness, and the presence of lubricants or contaminants.

Thus, in order to reduce wear (and consequently friction) **a thin film of lubricant** is inserted between the rubbing surfaces or **other materials** would be chosen with higher hardness.

Type of wear


Sliding wear
Abrasive (cutting) wear
2-Body
Multibody
Adhesive wear
Fatigue wear
Delamination
Fretting wear
Polishing wear
Impact wear
2-Body impact wear
Multibody impact wear
Erosion
Solids
Liquids
Gases
Slurries
Electric sparks
Cavitation
Bubbles (jets)
Rolling contact wear
Pure rolling contact
Rolling/sliding contact

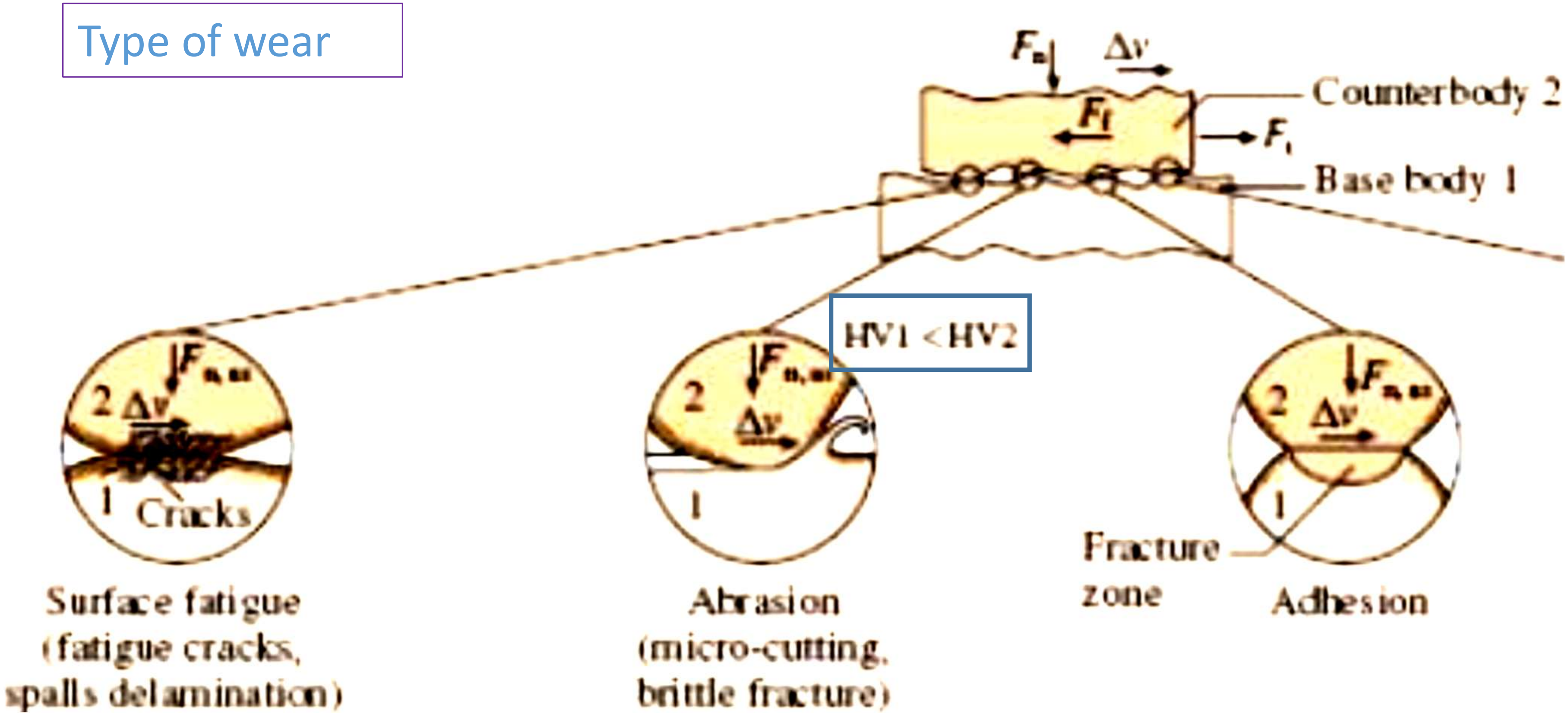
Wear Mechanisms

- Wear can be classified based on the ways that the frictional junctions are broken, that is, elastic displacement, plastic displacement, cutting, destruction of surface films and destruction of bulk material. There are many types of wear mechanisms, but we shall discuss about common wear mechanisms, which are:

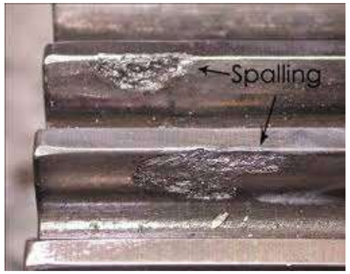
Types of wear

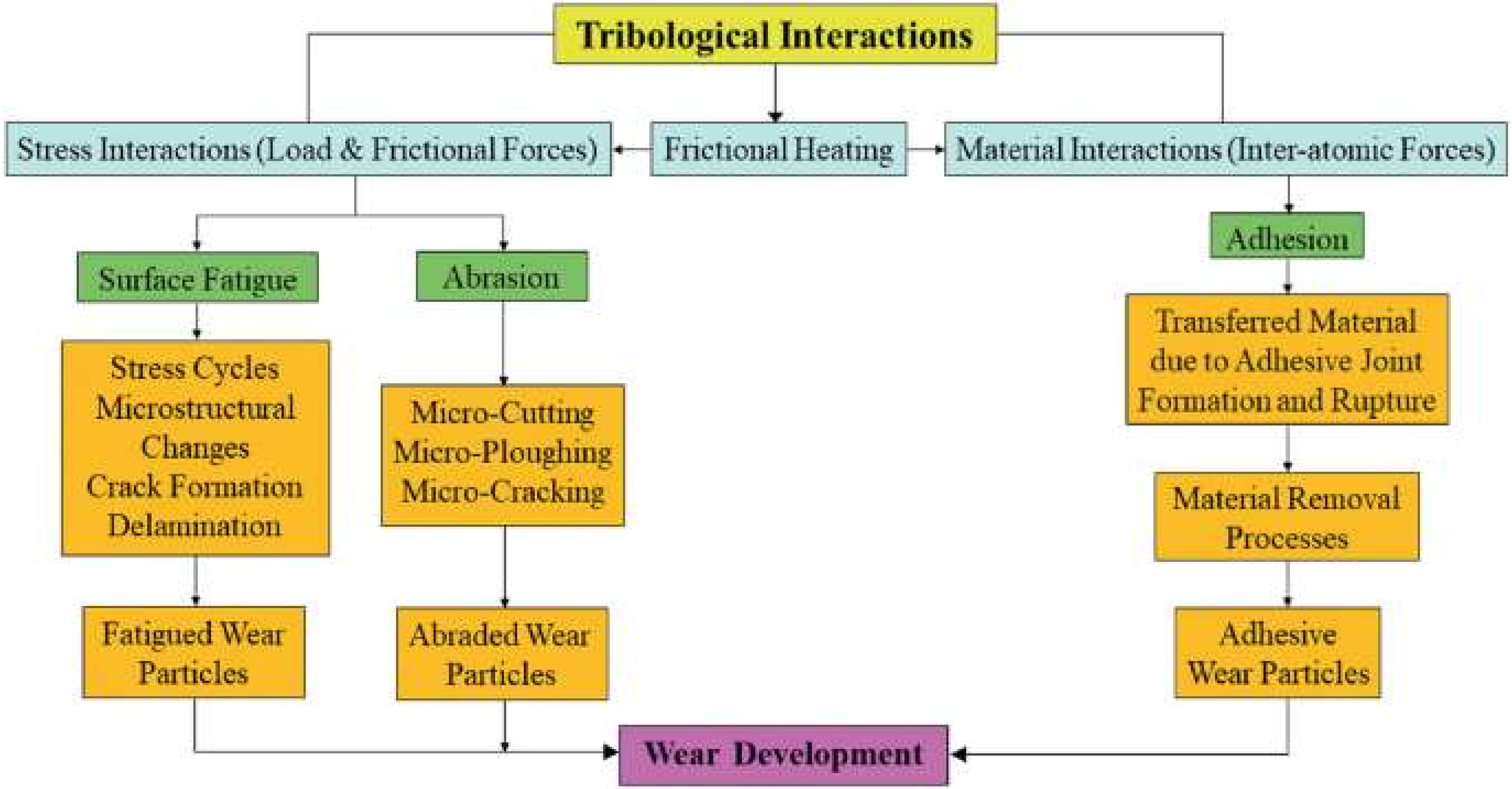
- Adhesive wear
  - Abrasive wear
    - Surface fatigue

Type of wear

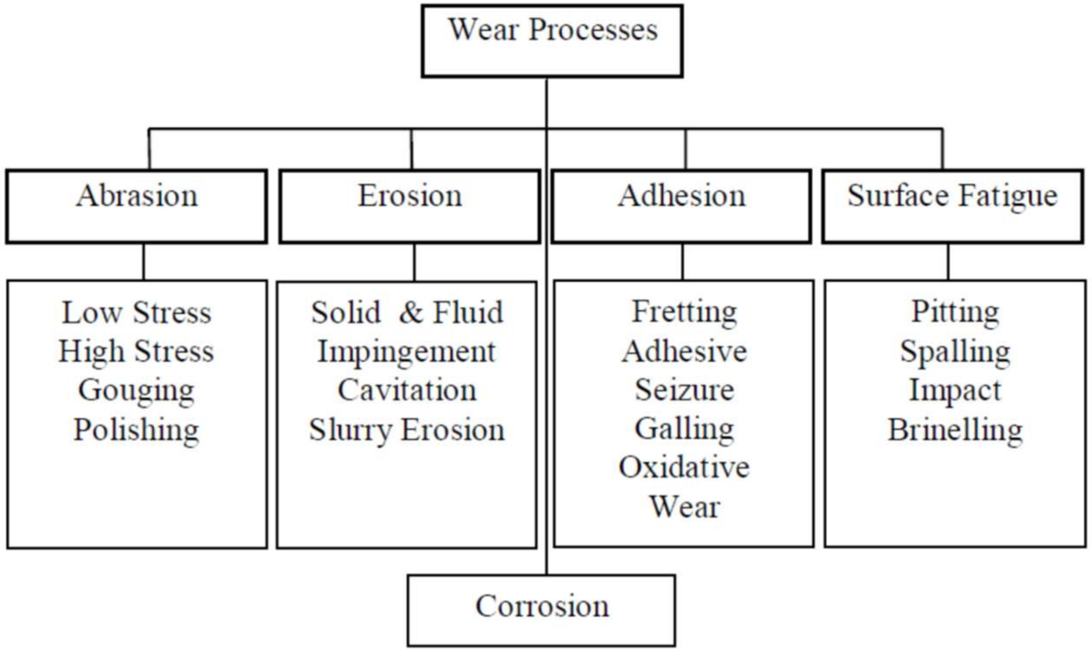


HV1 < HV2



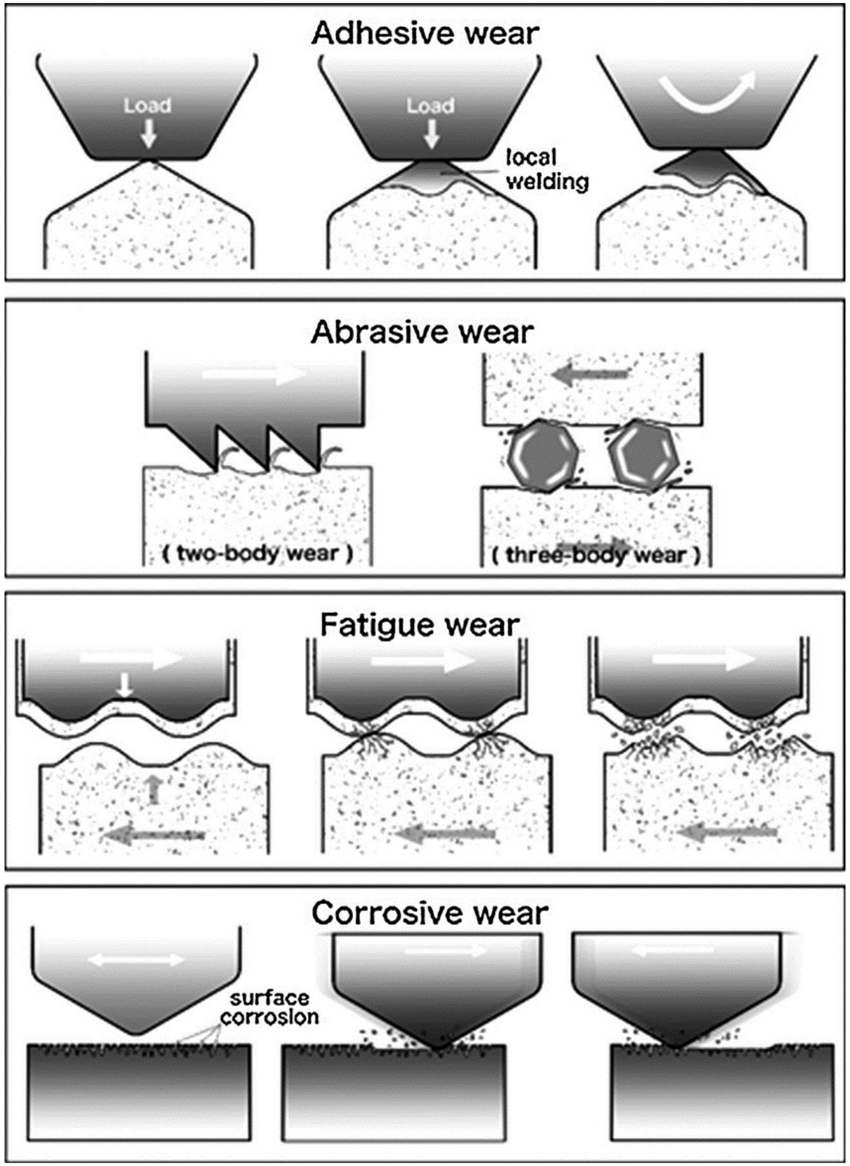

Tribological Interactions
Stress Interactions (Load & Frictional Forces)
Frictional Heating
Material Interactions (Inter-atomic Forces)
Surface Fatigue
Abrasion
Adhesion
Stress Cycles
Microstructural Changes
Crack Formation
Delamination
Micro-Cutting
Micro-Ploughing
Micro-Cracking
Transferred Material due to Adhesive Joint Formation and Rupture
Material Removal Processes
Fatigued Wear Particles
Abraded Wear Particles
Adhesive Wear Particles
Wear Development

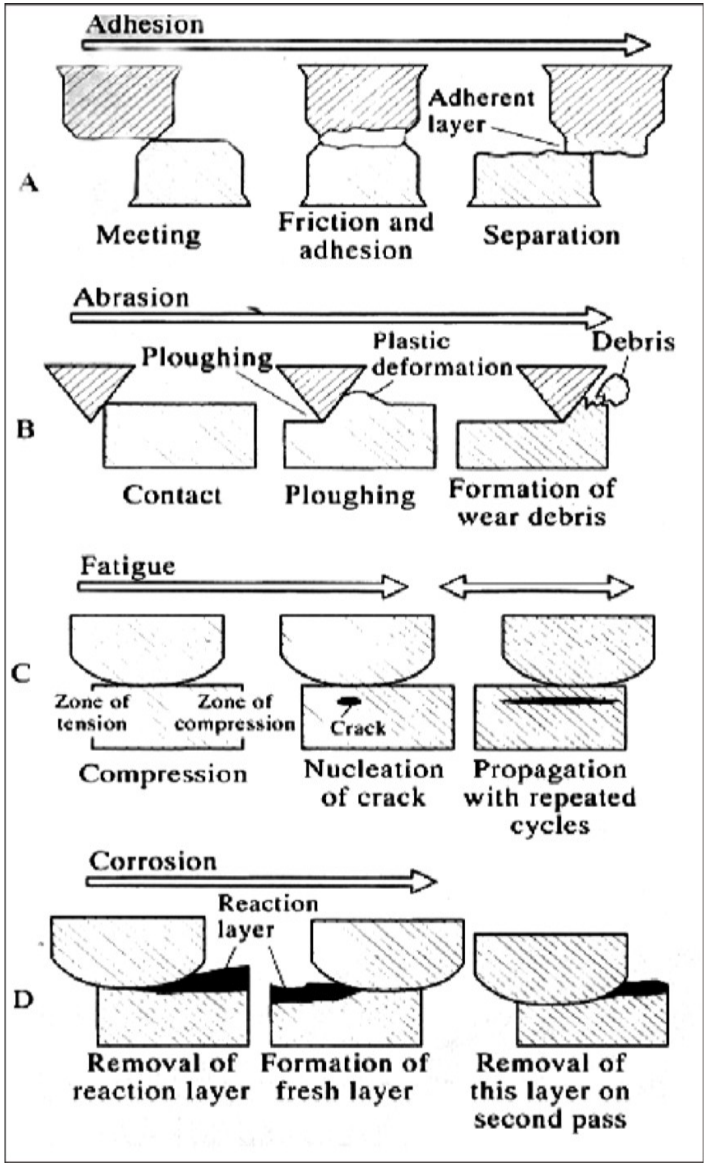
Types of wear process



- Erosive wear is caused by the impact of particles against a solid surface.
- Cavitation wear is caused by the localized impact of fluid against a surface or fast flowing fluids.

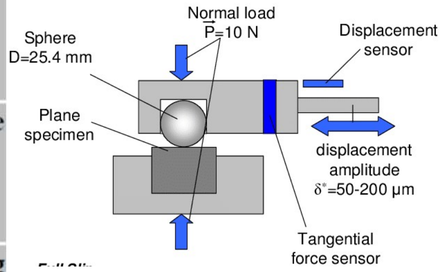
Type of wear


Adhesive wear
Load
Load
local welding
Abrasive wear
(two-body wear)
(three-body wear)
Fatigue wear
Corrosive wear
surface corrosion

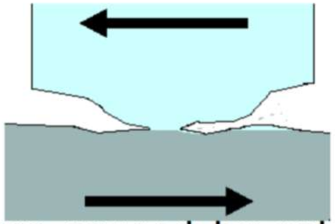

Adhesion
A
Meeting
Friction and adhesion
Adherent layer
Separation
Abrasion
B
Ploughing
Plastic deformation
Debris
Contact
Ploughing
Formation of wear debris
Fatigue
C
Zone of tension
Zone of compression
Crack
Compression
Nucleation of crack
Propagation with repeated cycles
Corrosion
D
Reaction layer
Removal of reaction layer
Formation of fresh layer
Removal of this layer on second pass

CLASSIFICATION OF WEAR

Type	Typical characteristics and definitions	observed In
Sliding wear (delamintation wear)	**Wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or the loss from either surface.** **Plastic deformation, crack nucleation and propagation in the surface**	**Sliders, bearing, gears and camshaft.**
Fretting wear	**Wear arising as a result of fretting (Small amplitude oscillatory motion, usually tangential, between two solid surfaces in contact).**	**Press fit parts with a small relative Sliding motion**
Abrasive wear	**Wear due to hard particles or hard protuberances forced against and moving along a solid surface.**	**Sliding surfaces ,earth-removing Equipment**
Erosive wear (solid particle impingement)	**Wear due to mechanical interaction between that surface and a fluid, a multi component fluid, or impinging liquid or solid particles**	**Turbine, pipes for coal slurries and helicopter blades**
Fatigue wear	**Wear of a solid surface caused by fracture arising from material fatigue.**	**Ball bearing, roller bearing glassy solid slider**
Cavitation wear	**A form of erosion causing material to wear by the action of vapour bubbles in a very turbulent liquid.**	**Soft Bearing Surfaces**



Adhesive wear



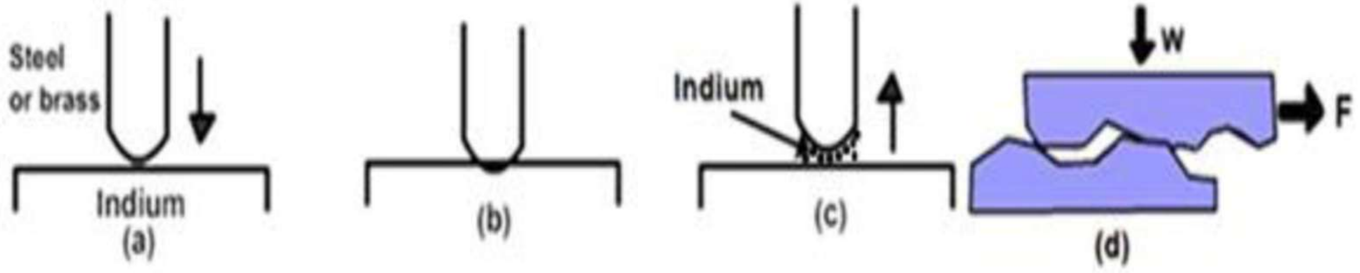
Adhesive wear are caused by relative motion, "direct contact" and plastic deformation which create wear debris and material transfer from one surface to another.

Example of Adhesive Wear:

- A Shaft rotating in a bushing
- Chalk on board-while writing

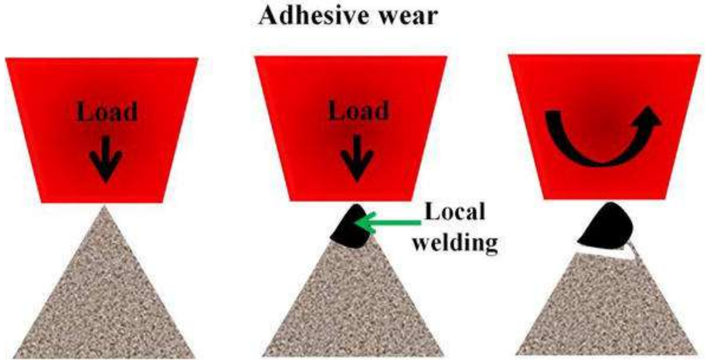
Adhesion Wear

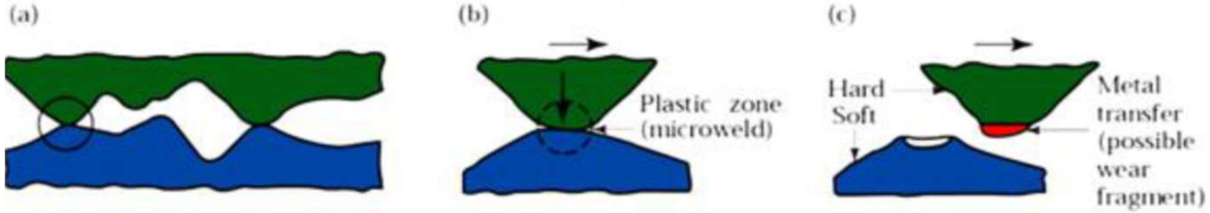
- Adhesive wear is very common in metals. It is heavily dependent on the mutual affinity between the materials. Let us take example of steel and indium.
- When steel pin under load is pushed [Fig. 3.5(b)] in indium block, and subsequently retracted, a thin layer of indium transferred on the steel pin.

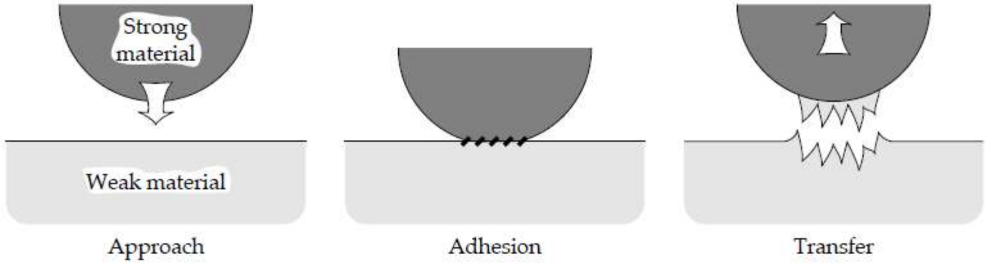


Steps in Adhesion Wear

1. Initial Contact and Asperity Interaction
2. Formation of Adhesive Junctions
3. Relative Motion and Shear Stress
4. Material Transfer or Detachment
5. Accumulation and Propagation



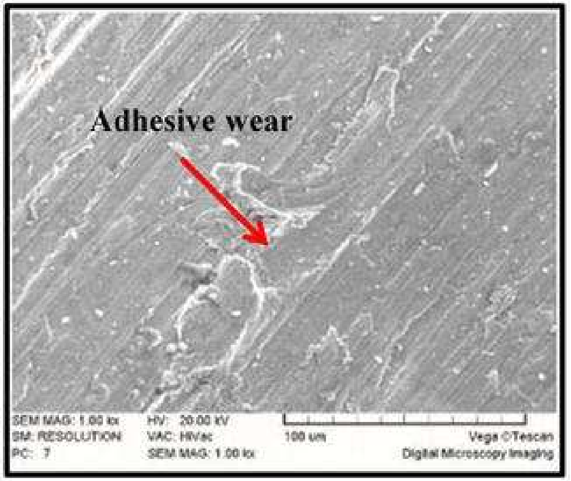


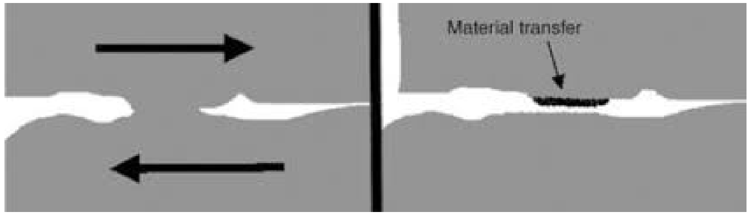


Adhesive wear is particularly **dominant in industrial components** where **metal-to-metal contact under load and relative motion** is frequent. It is a critical concern in systems lacking sufficient lubrication or operating under extreme conditions (high pressure, temperature, or speed).

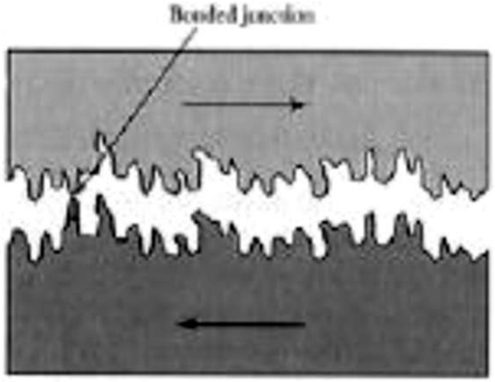
1. Hydraulic and Pneumatic Pistons/Cylinders
2. Gears (spur, helical, worm)
3. Bearings (especially plain or journal bearings)
4. Camshafts and tappets
5. Extrusion and Forming Dies
6. Compressors and Pumps (especially reciprocating types)
7. Electrical Contacts
8. Rail/Wheel Contacts

Adhesive wear

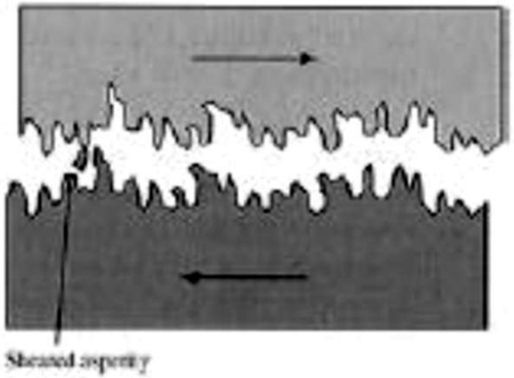




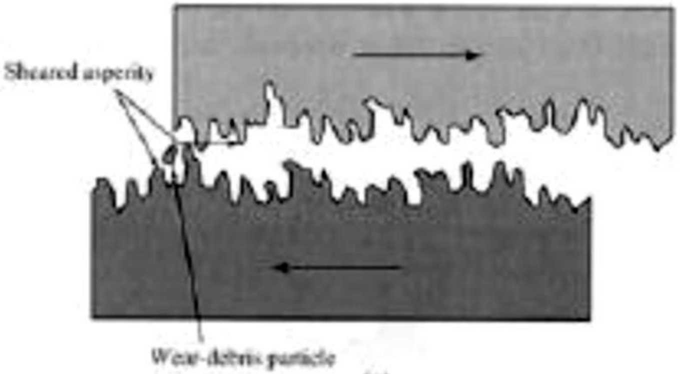
The sequence of steps occurring during adhesive wear:



(*a)* High local stresses plastically deform the material in the vicinity of the contact points, resulting in the formation of atomic bonds across the interface.



(b) As the force causing the relative sliding motion is increased, the shear stress in the joined region increases until it exceeds the shear strength of one of the solids.



(c) Subsequently, material is lost into the region between the two solids.

Laws of Adhesive Wear

1. Wear Volume proportional to sliding distance of travel (L)
   - *True for wide range of conditions*

2. Wear Volume proportional to the load (W)
   - *Dramatic increase beyond critical load.*
3. Wear volume inversely proportional to hardness(H) of softer material

Archer's Adhesion Wear Model

As per adhesion wear laws, wear volume is given by $V = K_1WL/3H$. This equation is known as **Archard's Wear** Equation.

The value of k_1 depends on;

- *elastic-plastic contacts,*
- *shearing of those contacts,*
- *effect of environment,*
- *mode of lubrication, etc.*

Wear Measurement

- Archard wear Equation :

$$W \alpha \frac{w}{H}$$

w =*wear*

w = *Normal Load on contact*

H= *surface hardness of the wearing material*

K= *wear coefficient (dimensionless)*

$$W = K \frac{w}{H}$$

$\frac{K}{H}$ = is called Dimensional wear constant

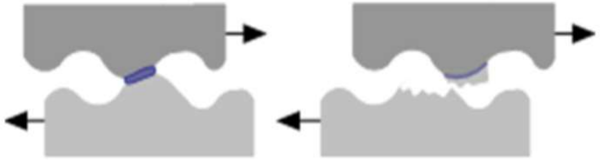
Unit =(volume)/(Load/meter)

Frictional wear / adhesive wear

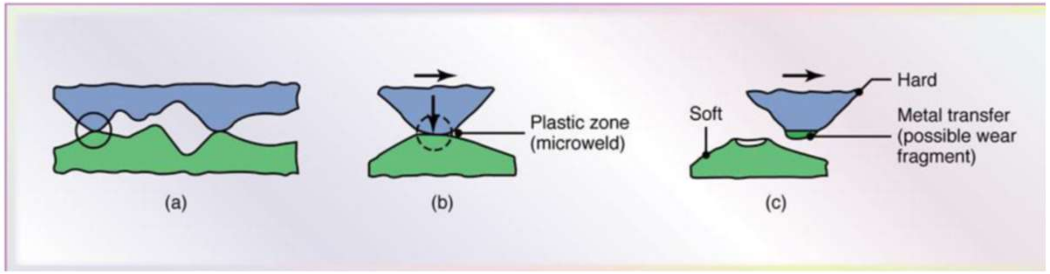
Two bodies sliding over or pressed into each other which promote the material transfer from one to another.

$$\frac{V}{L} = K\frac{P}{3\sigma y}$$

Where
V = wear volume
L = sliding velocity
P = applied load
σy = yield stress of softer material
K = wear coefficient



Ref.: www.substech.com



1. Material Properties

- **Hardness**: Generally, harder materials resist adhesive wear better, as they are less likely to plastically deform or transfer material.
- **Ductility**: Highly ductile materials can deform plastically at contact points, potentially increasing the extent of junction formation and material transfer.
- **Chemical Affinity**: Materials with a strong tendency to form bonds (e.g., similar metals) are more prone to adhesive wear.
- **Crystal Structure and Microstructure**: These affect how materials respond to stress and whether they favor ductile vs. brittle fracture under shear.

2. Surface Roughness and Topography

- Smoother surfaces reduce the number and severity of asperity contacts, minimizing adhesion.
- However, **very smooth surfaces** may paradoxically increase adhesive wear if they allow for large-area bonding (due to increased true contact area).
- Optimizing surface texture is therefore essential to balance friction and wear.

---

3. Load and Contact Pressure

- Higher normal loads increase the real area of contact (through asperity deformation), promoting stronger adhesive junctions.
- This can elevate both the **probability and severity** of adhesive wear.

4. Sliding Speed and Temperature

- Increased speed can raise local temperatures at contact points due to frictional heating.
- **Elevated temperature**:
    - Promotes material softening and plastic flow.
    - Enhances atomic diffusion, facilitating bonding.
    - May reduce or degrade protective surface films (like oxides or lubricants).

5. Lubrication

- A **well-designed lubrication system** is perhaps the most effective method for reducing adhesive wear.
- Lubricants:
    - Form a barrier that prevents direct metal-to-metal contact.
    - Carry away wear debris and dissipate heat.
    - May contain anti-wear or extreme pressure additives that form protective films.

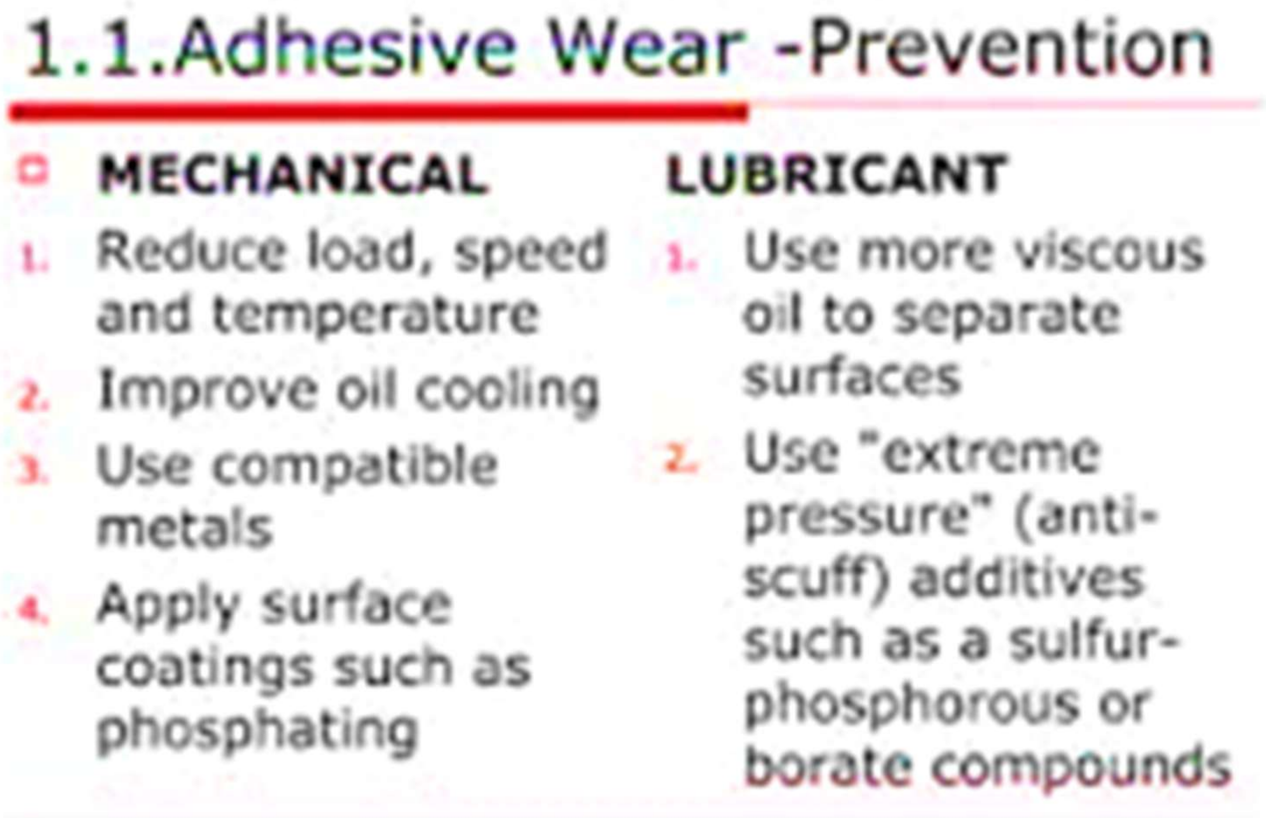
---

6. Surface Films and Oxide Layers

- Naturally forming oxide films (especially on metals like aluminum or stainless steel) can act as **protective barriers**, reducing adhesion.
- However, under certain conditions, these films can break down, leading to **metallic contact and adhesion**.

7. Environment and Contamination

- Humidity, corrosion, and the presence of contaminants (e.g., dust or debris) can modify surface chemistry or introduce third-body abrasion, influencing adhesive wear behavior.



1.1.Adhesive Wear -Prevention

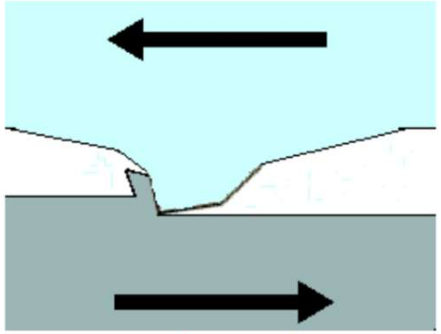
- **MECHANICAL**

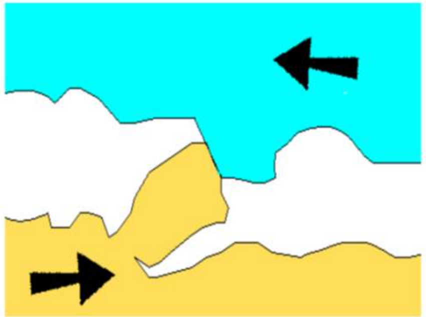
1. Reduce load, speed and temperature
2. Improve oil cooling
3. Use compatible metals
4. Apply surface coatings such as phosphating

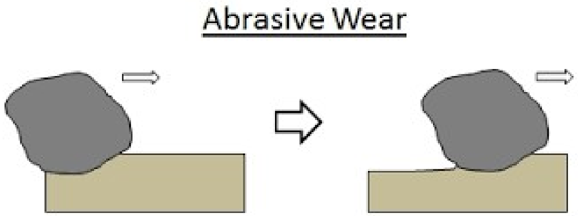
LUBRICANT

1. Use more viscous oil to separate surfaces
2. Use "extreme pressure" (anti-scuff) additives such as a sulfur-phosphorous or borate compounds

Abrasive Wear





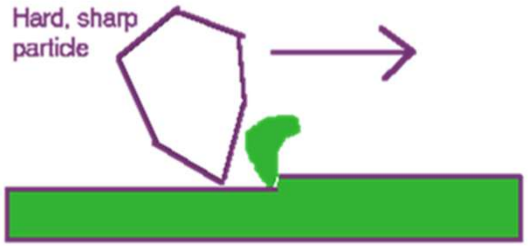


Abrasive wear occurs when a hard rough surface slides across a softer surface. ASTM International (formerly American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface.

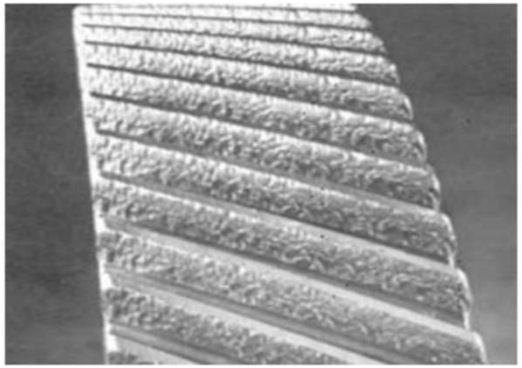
Definition of Abrasive Wear

Abrasion is the most common form (55-60%) of wear in industry.

- Abrasive wear occurs between surfaces of different relative hardness.
- Abrasive wear is caused by hard particles on the surface or within the work material such as inclusions.
- These particles act as micro cutting tools on a microscopic scale.



Abrasive Wear



- Abrasive wear, sometimes called cutting wear, occurs when hard particles slide and roll under pressure, across the tooth surface.
- Hard particle sources are: dirt in the housing, sand or scale from castings, metal wear particles, and particles introduced into housing when filling with lube oil.
- Scratching is a form of abrasive wear, characterized by short scratch-like lines in the direction of sliding. This type of damage is usually light and can be stopped by removing the contaminants that caused it. Fig. shows abrasive wear of a hardened gear.

Machines/ components affected by abrasive wear:

1-Cutting tools

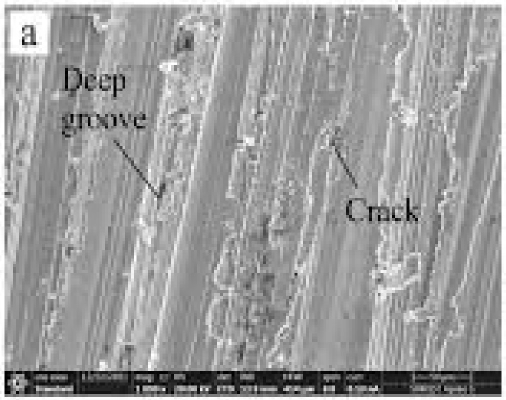
2-Machine component

- Piston/cylinders
- Journal bearings
- Gears
- Cams

3-Agricultural implements
- Swash plates
- Slurry pumps

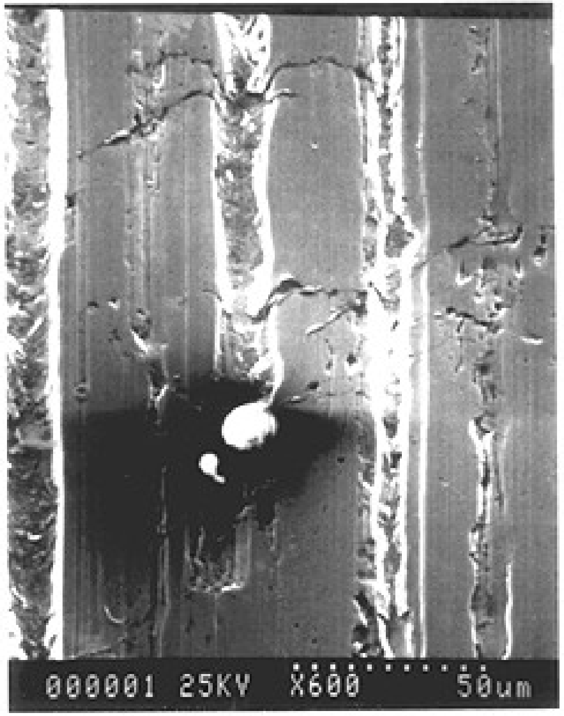
4-Digging tools
- Augers
- Scraper blades

High magnification of a punch edge shows a characteristic pattern caused by abrasive wear.



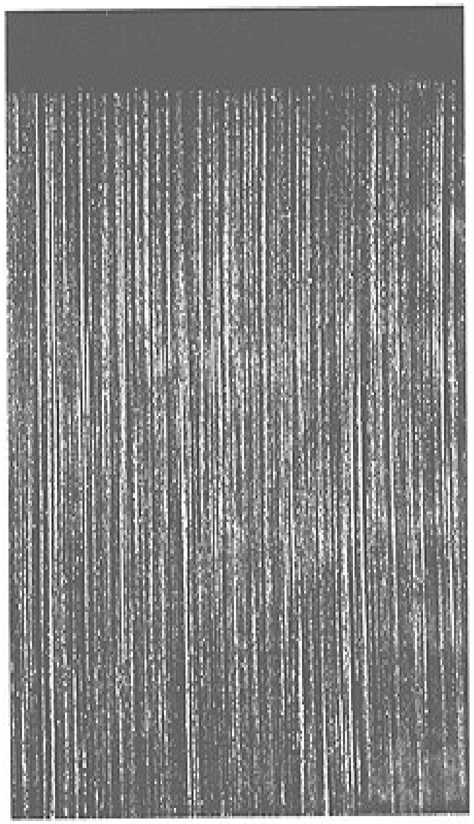
Marine Diesel Engine Piston Ring

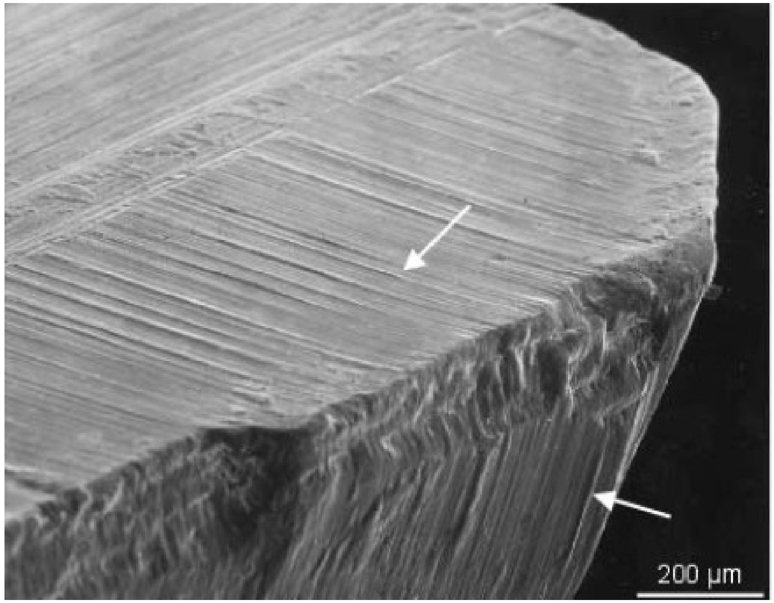
Magnification 400x



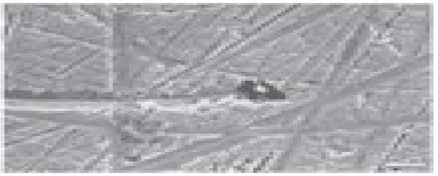
Magnification 600x

ABRASIVE WEAR
Gear Tooth






Imbedded Particle

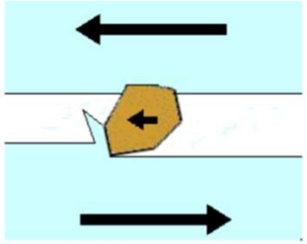

Scratch Marks

Abrasive wear in punch

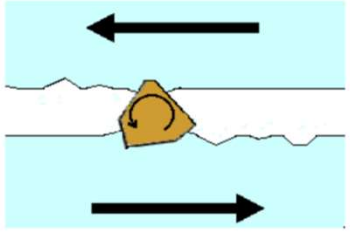
- Because of the motion between the punch and work material, small microchips are cut out of the tool, which leads to a gradual loss of tooling material.
- On a macroscopic level, this type of tool wear causes a rounding of the punch edge, yet the punch still appears relatively smooth.
- A closer inspection shows characteristic parallel scratch marks on the edge and along the sides of a punch where particles cut into the tool surface during the stamping.

Types of Abrasive wear

- Abrasive wear is commonly classified according to the type of contact and the contact environment
- The two modes of abrasive wear are known as two-body and three-body abrasive wear
- Two-body wear occurs when the grits or hard particles remove material from the opposite surface.
- Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface.



Two-body wear



Three-body wear

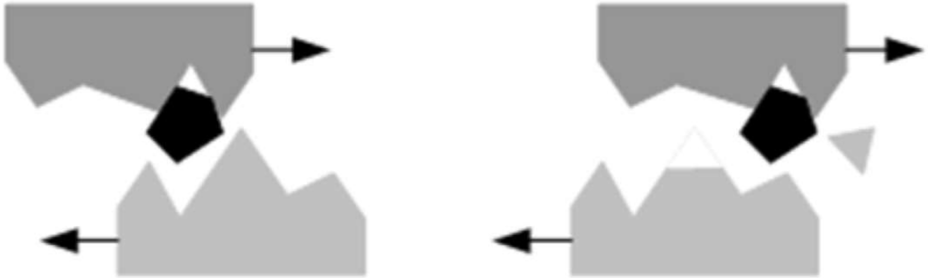
Two-body systems typically experience from 10 to 1000 times as much loss as three-body systems for a given load and path length of wear.

Abrasive wear

Abrasive wear occurs when a harder material is rubbing against a softer material

Two body wear

Three body wear



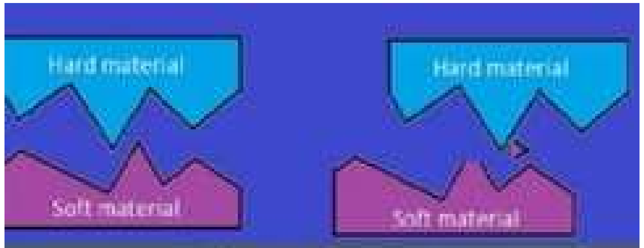
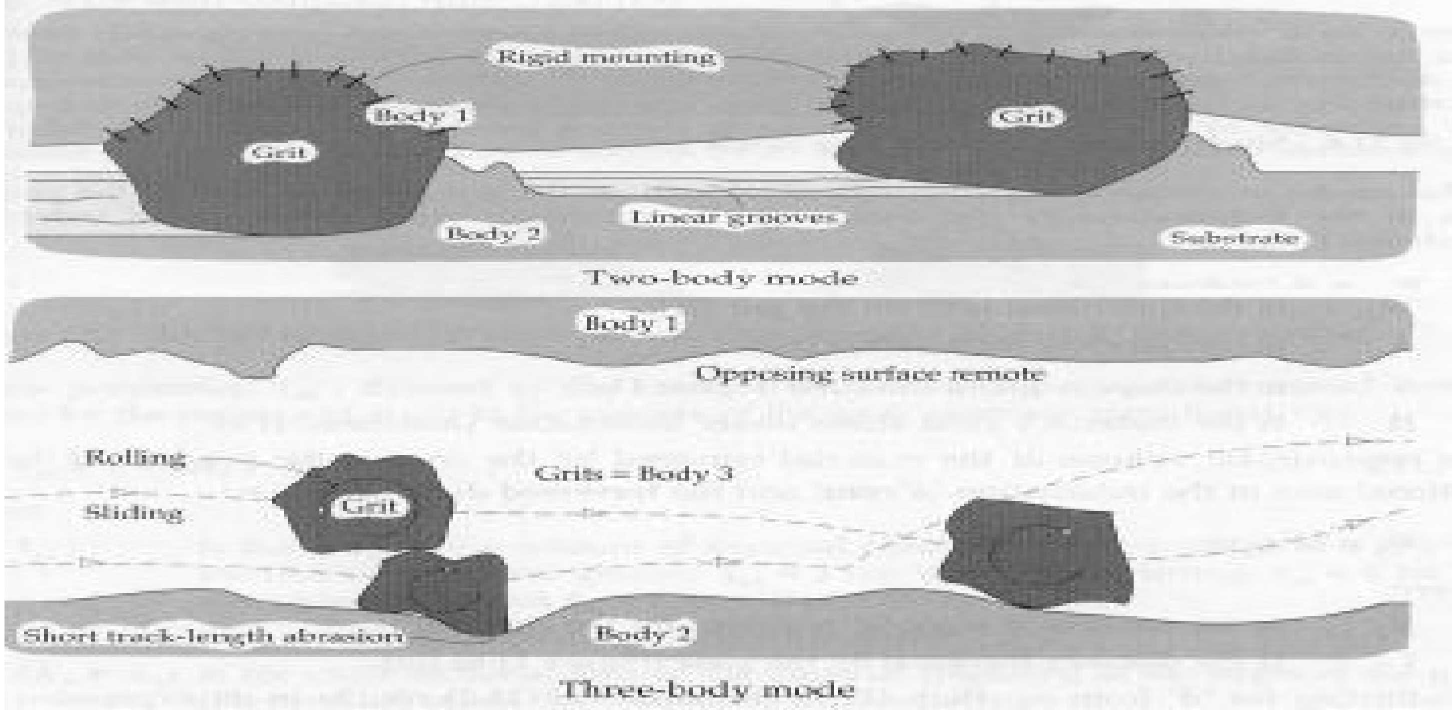


Fig 3. Abrasive Wear Mechanism

Types of Abrasion (environment mode)

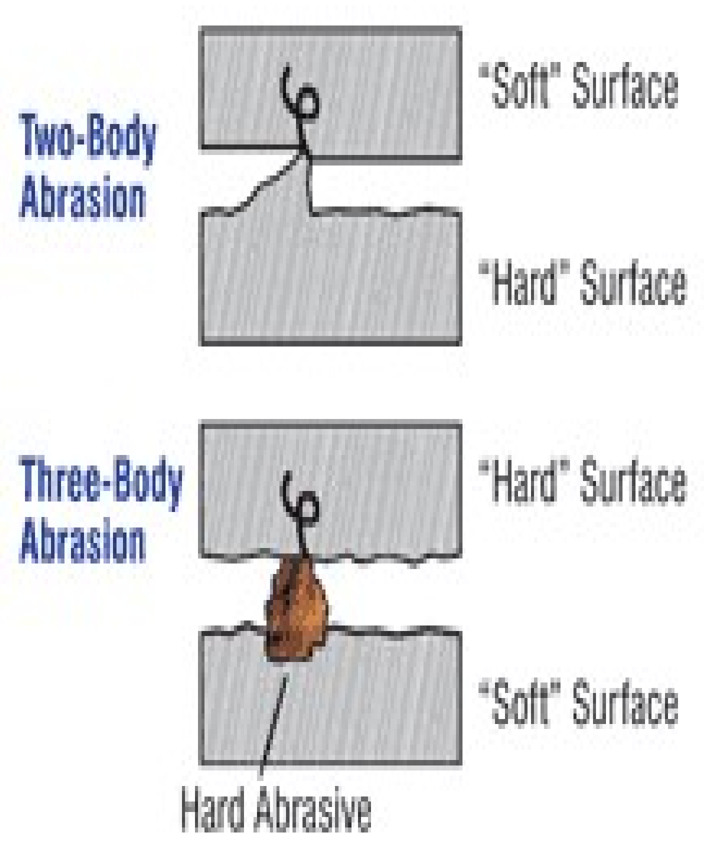
Closed mode of wear is ten times faster than open body mode

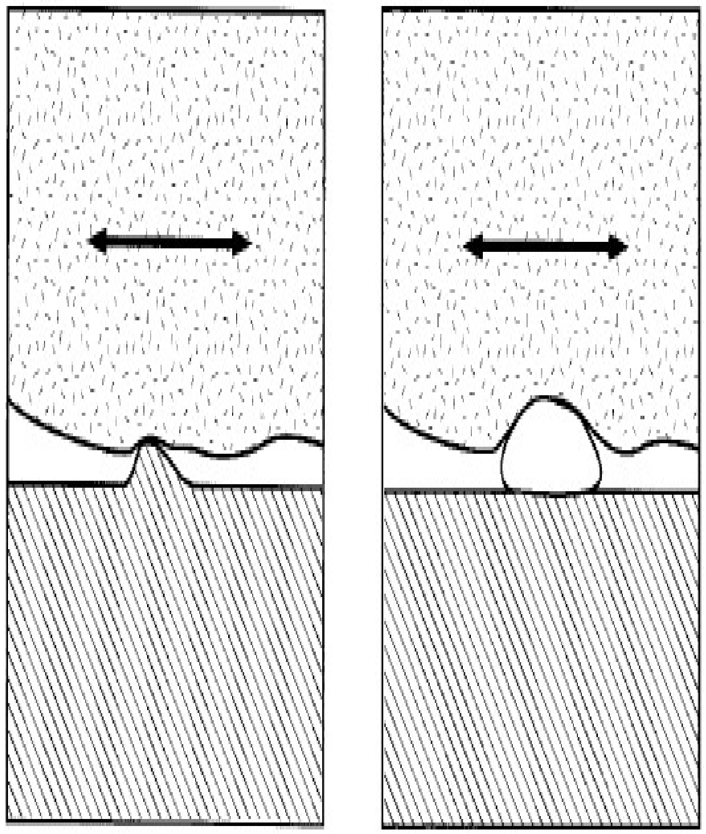
Two-body wear occurs when the grits, or hard particles, are rigidly mounted or adhere to a surface



Three-body wear occurs when the particles are not constrained and are free to roll and slide down a surface

Abrasive Wear type





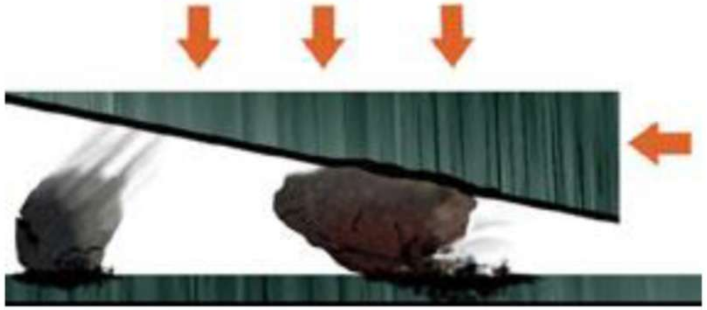
Types of Abrasion (Stress mode)

- Gouging (impact Stress)
- Grinding (High-Stress)
- Scratching (Low-Stress)

Types of abrasive wear

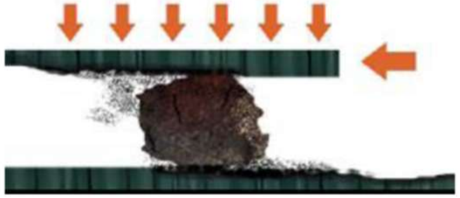
Gouging abrasion

- Large particles
- High compression loads



High stress or grinding abrasion

- Smaller particles
- High compression load



Low stress or scratching abrasion

- No compression load
- Scratching abrasion while material is sliding

Polishing abrasion

Gouging (impact Stress)

The resulting wear can be extreme when high-stress or low stress abrasions are accompanied by some degree of impact and weight.

The metal surface receives prominent gouges and grooves when massive objects (often rock) are forced with pressure against them.

Grinding (High-Stress)

This is more intense than simple scratching or less than gouging.
It happens when small, hard, abrasive particles are forced against a metal surface with enough force to crush the particle in a grinding mode. Most often the compressive force is supplied by two metal components with the abrasive sandwiched between them.

Even with low nominal loads on the metal portion of this sandwich the unit stresses in the abrasive, and consequently on its metallic contact areas, may be very high.

These stresses crack or crush the abrasive grains.

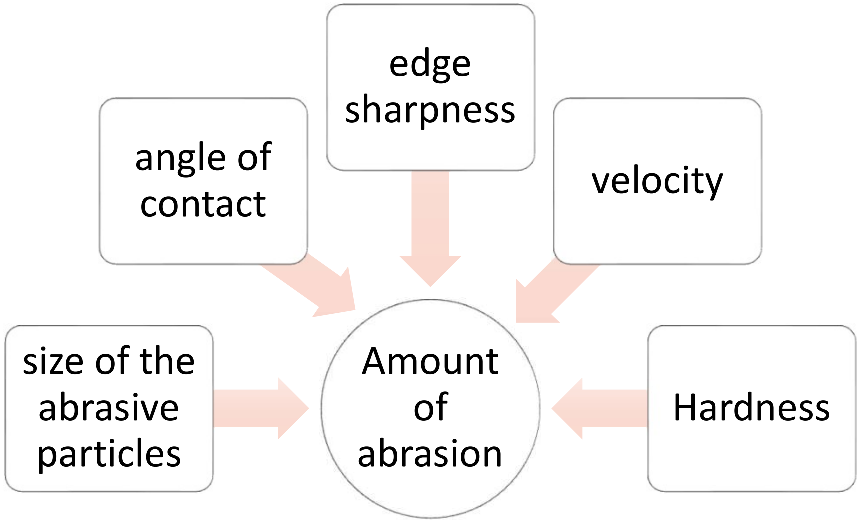
The broken edges are sharp and can

- score effectively
- local plastic flow
- surface micro-cracking

Scratching (Low-Stress)

This is normally the least severe type of abrasion. Metal parts are worn away through the repeated scouring action of hard, sharp particles moving across a metal surface at varying velocities.

The abrasive may be present within the product, either as a filler or a pigment. (glass fibers in plastics) such products suffer what is called:
”Low Stress Abrasive Wear”

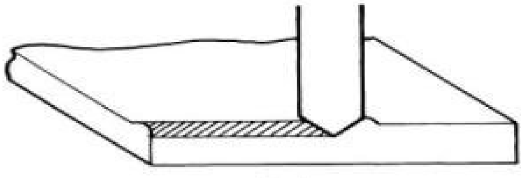


Mechanisms of abrasive wear

- Plowing
- Cutting
- Fracture

Mechanisms of abrasive wear

Plowing



Plowing

Plowing occurs when a material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles

Displacing material to the sides of the groove formed. This process doesn't necessarily remove material from the surface, but it can lead to significant surface damage and deformation.

Key Factors Influencing Plowing:

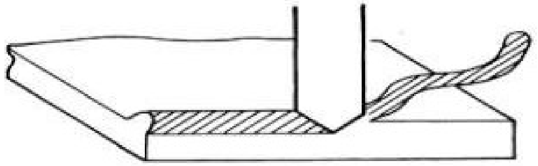
- **Hardness Disparity:** A significant difference in hardness between the abrasive particle and the surface material is crucial. The harder particle must be able to penetrate and displace the softer material.
- **Particle Shape:** Blunt particles are more likely to induce plowing as they push material aside. Sharper particles tend to cut into the material, leading to a different wear mechanism.
- **Load:** Light loads favor plowing, as the particle doesn't have enough force to penetrate deeply and remove material. As the load increases, the mechanism may transition to cutting or other more severe forms of wear.
- **Surface Conditions:** The surface roughness and the presence of lubricants can influence the extent of plowing. A smoother surface and the presence of a lubricant can reduce friction and mitigate the severity of plowing.

Mitigating Plowing:

- **Material Selection:** Choosing materials with higher hardness and wear resistance can help reduce the impact of plowing.
- **Surface Treatments:** Hardening treatments, such as case hardening or nitriding, can increase the surface hardness and resistance to wear.
- **Lubrication:** Proper lubrication can reduce friction and minimize the severity of plowing.
- **Particle Control:** Filtering the working environment to remove abrasive particles can significantly reduce wear.

Cutting

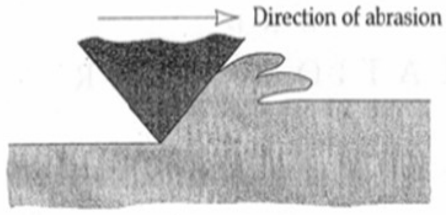
In abrasive wear, the cutting mechanism occurs when a sharp, hard particle penetrates the surface of a softer material, removing material in the process. This is analogous to using a knife to cut through a piece of bread.



Cutting

Key Factors Influencing Cutting:

- **Particle Shape:** Sharp-edged particles are more likely to cause cutting, as they can easily penetrate the surface.
- **Particle Hardness:** The particle must be significantly harder than the the surface material to effectively cut into it.
- **Load:** A sufficient load is required to force the particle into the surface and remove material.



a) Cutting

Impact of Cutting:

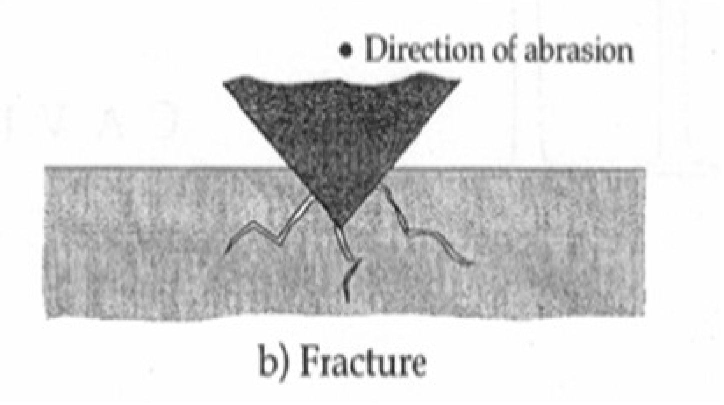
Material Removal: Cutting directly removes material from the surface, leading to a loss of material and a reduction in component thickness.

Surface Roughening: The cutting process creates grooves and scratches on the surface, increasing surface roughness and reducing the load-carrying capacity.

Fracture

Wear fatigue is a type of wear that occurs due to cyclic stresses on the surface of a material. Over time, these cyclic stresses can lead to the initiation and propagation of cracks, eventually resulting in the removal of material from the surface.

Fragmentation causes localized fracture of the wear material



b) Fracture

Factors Affecting Wear Fatigue:

Material Properties: The mechanical properties of the material, such as hardness, yield strength, and fatigue strength, influence its resistance to wear fatigue.
Surface Finish: A smoother surface can reduce stress concentrations and delay crack initiation.
Lubrication: Proper lubrication can reduce friction and wear.
Load: Higher loads can increase the severity of cyclic stresses.
Sliding Speed: Higher sliding speeds can accelerate wear.

In the micro-level, abrasive action results in one of the following wear modes:

- **Ploughing**. The material is shifted to the sides of the wear groove. The material is not removed from the surface.
- **Cutting**. A chip forms in front of the cutting asperity/grit. The material is removed (lost) from the surface in the volume equal to the volume of the wear track (groove).
- **Cracking (brittle fracture)**. The material cracks in the subsurface regions surrounding the wear groove. The volume of the lost material is higher than the volume of the wear track.

Mechanism of Abrasive Wear

a) Cutting

b) Fracture

c) Fatigue by repeated ploughing

d) Grain pull-out

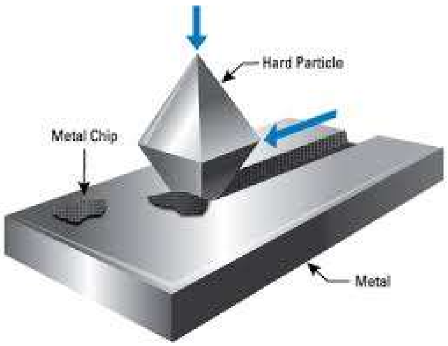
Fig. *Mechanisms of abrasive wear: microcutting, fracture, fatigue and grain pull-out*

Grain pull-out is a specific type of abrasive wear mechanism that primarily affects ceramic materials.
It occurs when a hard abrasive particle interacts with the surface of a ceramic material, causing individual grains to detach from the surface.

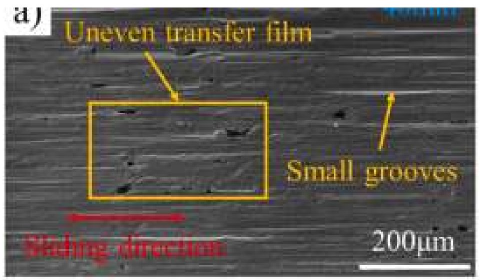
Grain Detachment: If the stress concentration exceeds the bonding strength between the grains, the grain can detach from the surface.

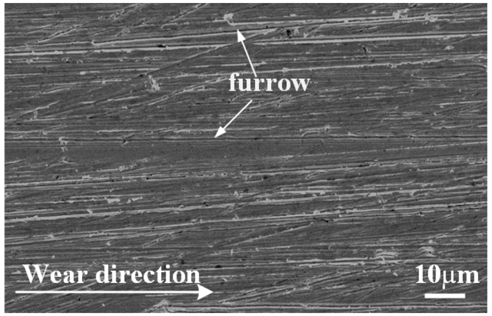
Factors Affecting Grain Pull-Out:
Grain Size and Distribution: Smaller grain sizes generally lead to higher wear resistance, as smaller grains have stronger intergranular bonds.
Grain Boundary Strength: The strength of the bonds between grains significantly influences the resistance to grain pull-out.
Hardness of the Abrasive Particle: Harder abrasive particles are more likely to cause grain pull-out.
Loading Conditions: Higher loads and sliding speeds can increase the likelihood of grain pull-out.

The consequences of abrasive wear are:



- Grooves
- Scratches marking
- Micro-chips
- Furrows
- Leakage
- Lower efficiency
- Dimensional changes
- Shiny spots on textured tool surfaces

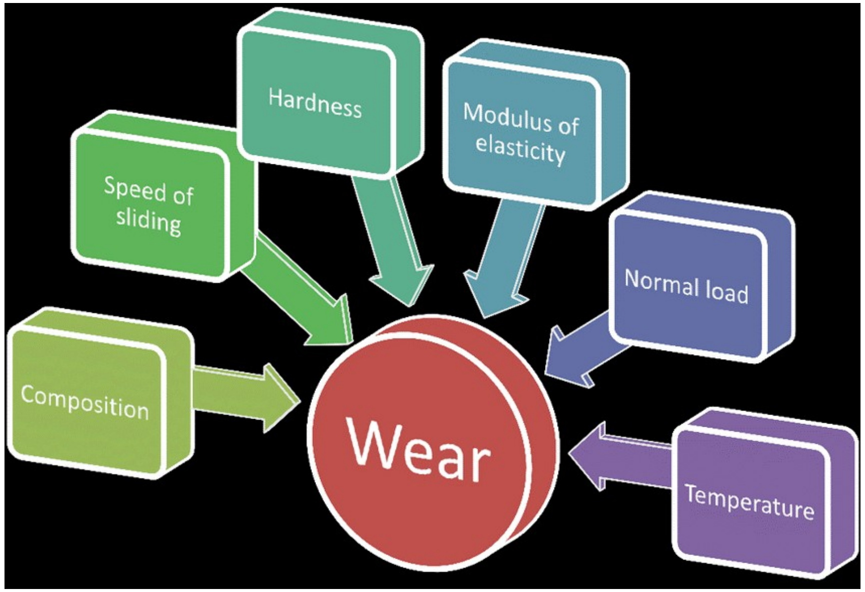




Wear Dependence

For Dry/unlubricated surfaces sliding

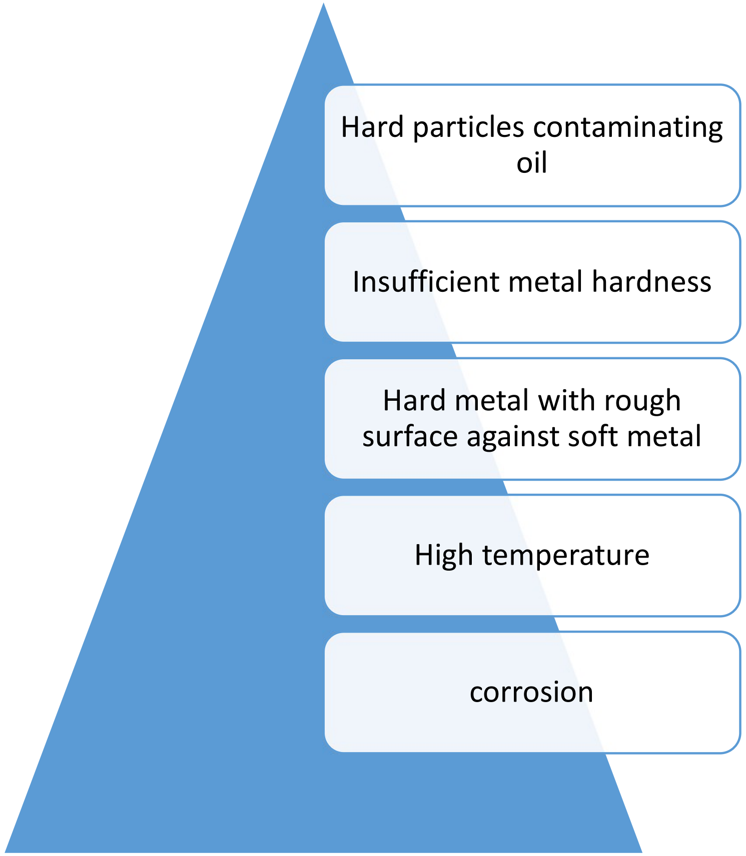
- Normal Load
- Relative sliding speed
- The initial temperature
- Thermal, Mechanical , chemical properties of the material in contact
- No simpler Model to explain wear



Occurrence of Wear depends on

- ★ Geometry of the surface
- Applied load
- The rolling and sliding velocities
- Environmental conditions
- Mechanical, Thermal, Chemical and Metallurgical properties
- ★ Physical, Thermal and Chemical properties of the lubricant

Conditions Promoting Wear

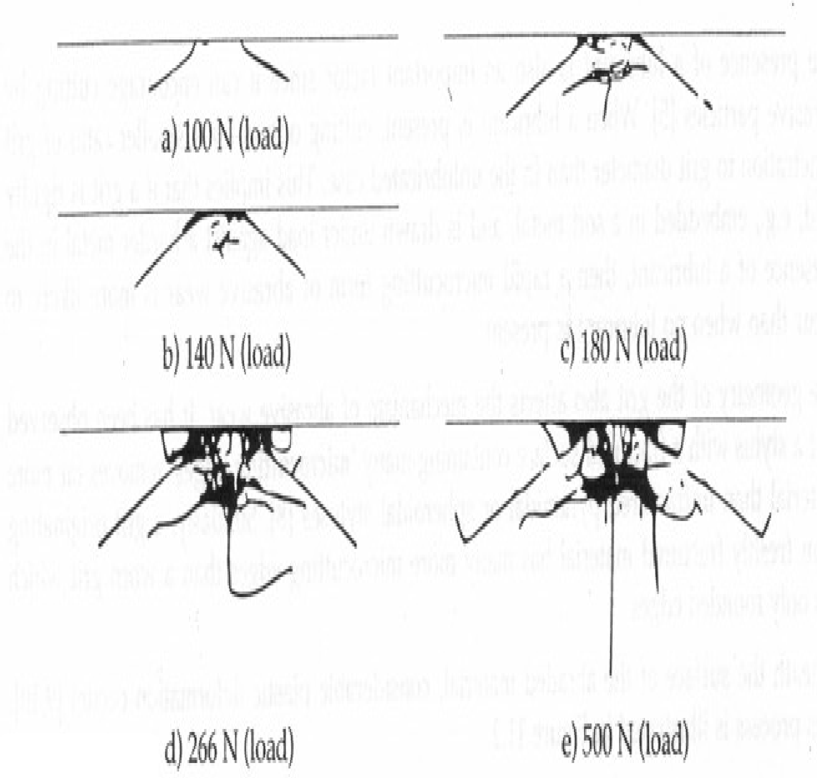


- Hard particles contaminating oil
- Insufficient metal hardness
- Hard metal with rough surface against soft metal
- High temperature
- corrosion

Influencing factors:

- **Load**
- **Particle size/ hardness**
- **Particle shape**
- **Surface hardness**
- **Temperature**
- **Viscosity**
- Moisture

Load effect



a) 100 N (load)

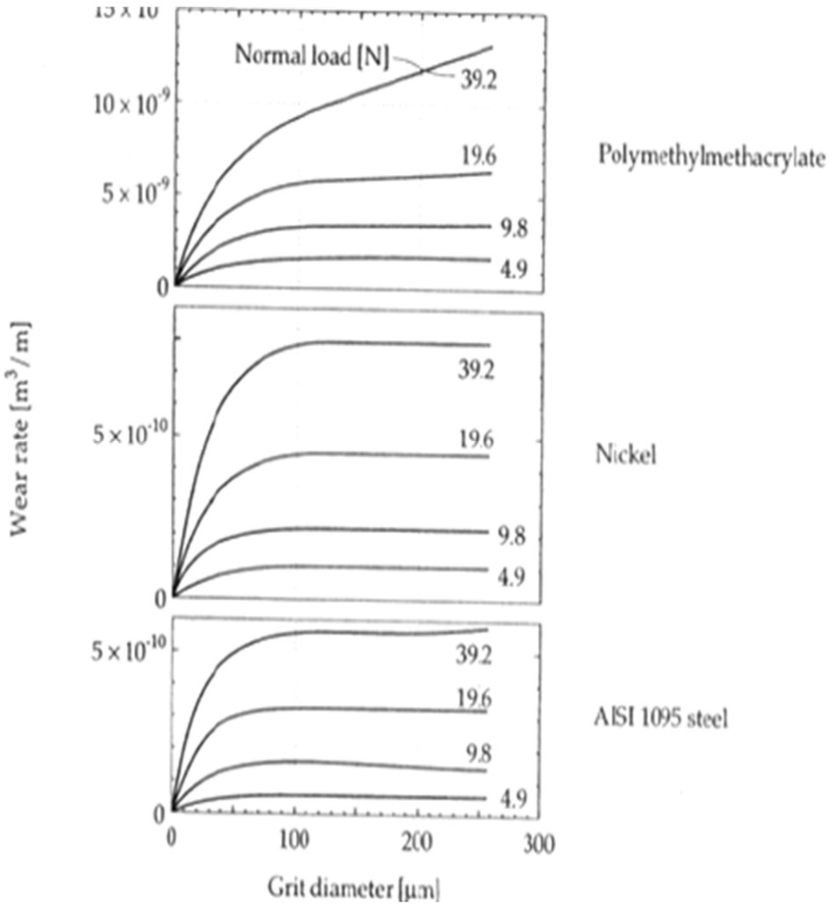
b) 140 N (load)

c) 180 N (load)

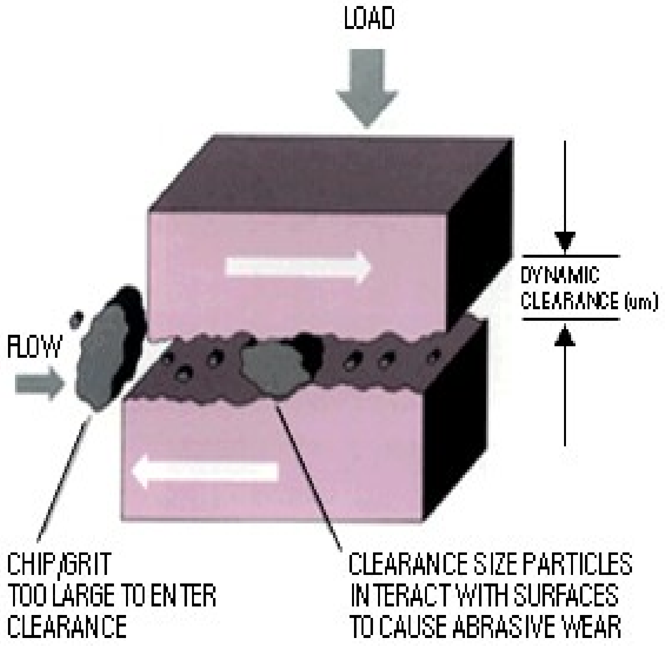
d) 266 N (load)

e) 500 N (load)

FIGURE 11.3 Generation of cracks under an indenter in brittle solids (adapted from [12]).

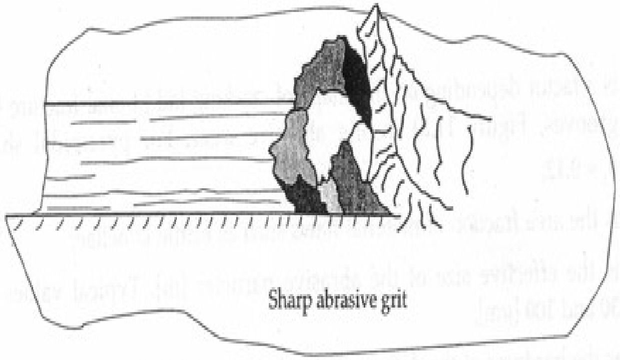


Debris size effect

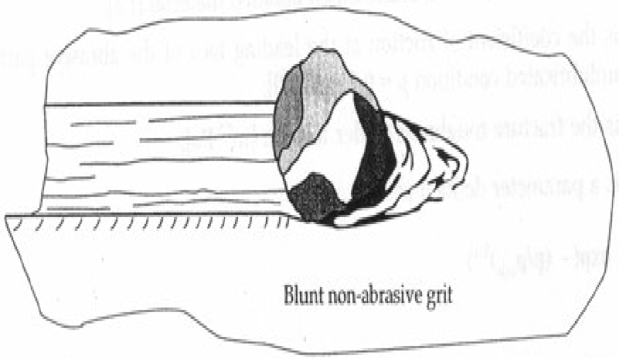


The particle sizes causing the most damage are those equal to and slightly larger than the clearance space.

Bluntness effect

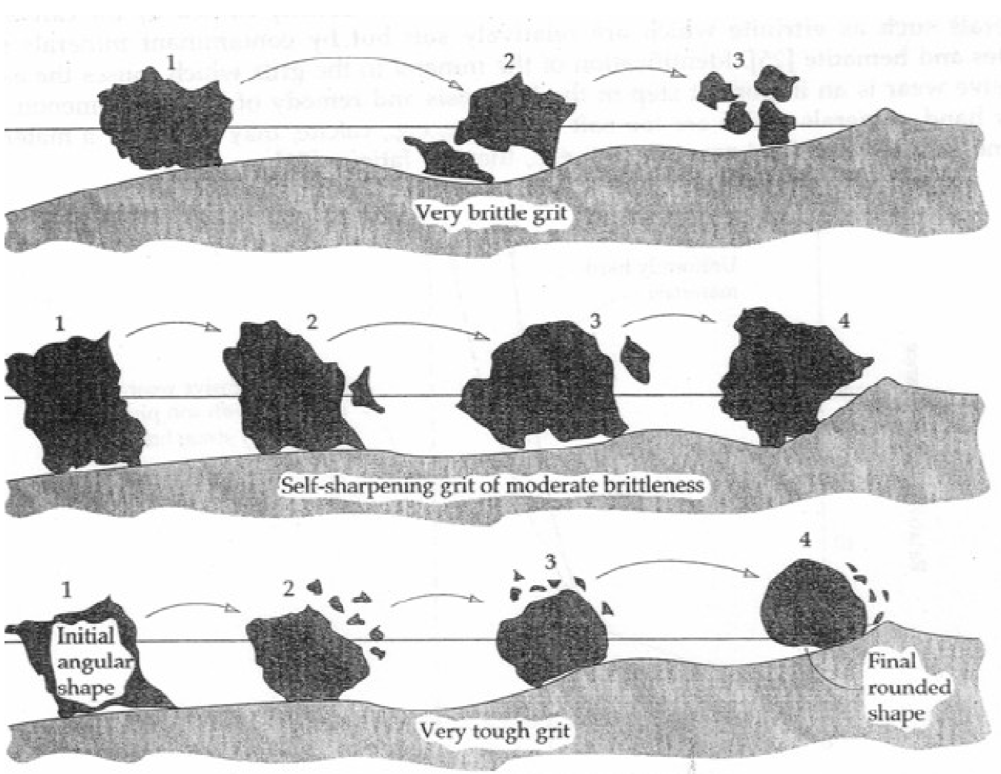


Sharp abrasive grit



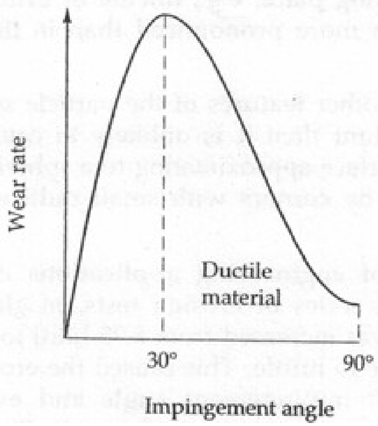
Blunt non-abrasive grit

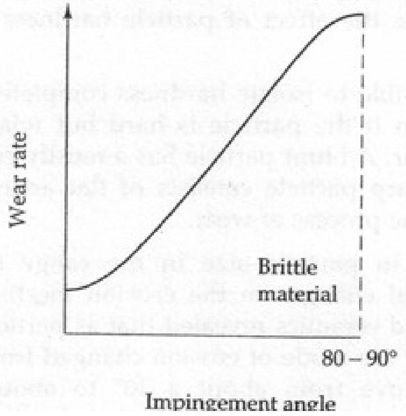
Hardness and contact angle effect



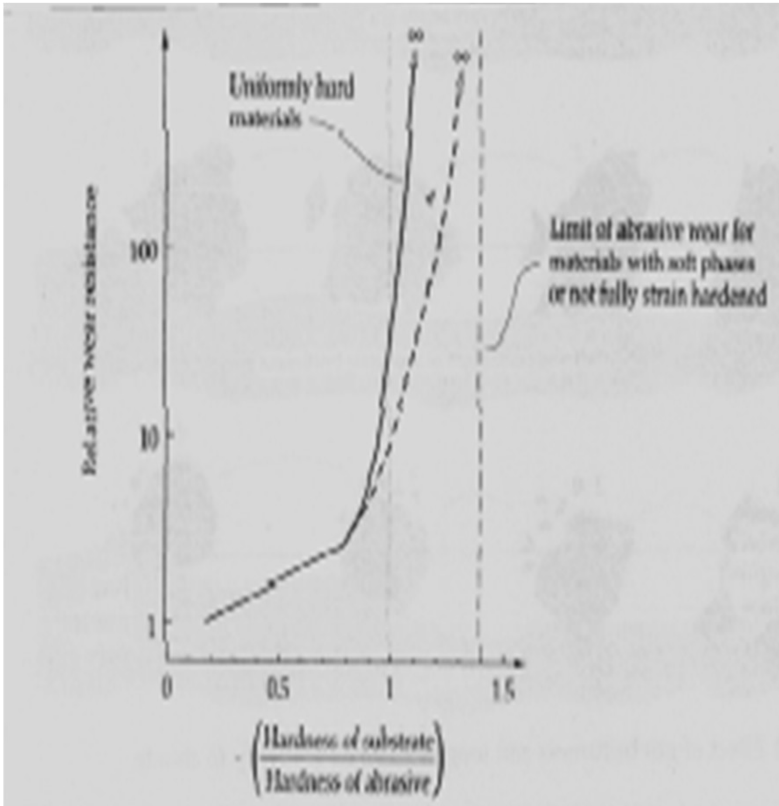
11.12 Effect of grit brittleness and toughness on its efficiency to abrade.

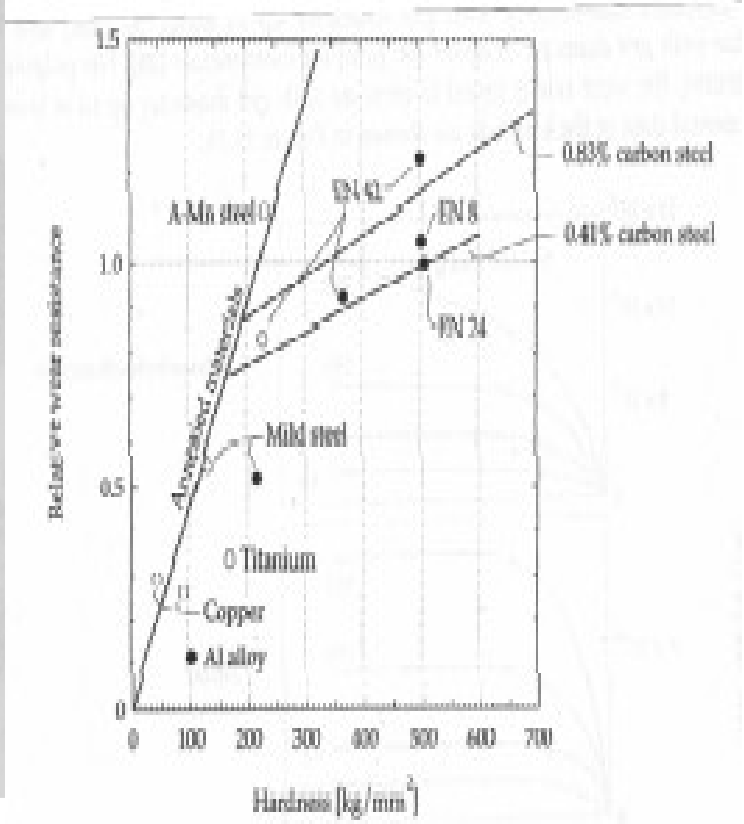
If the surface is harder than the particle, the wear rate is minimal.





Hardness effect

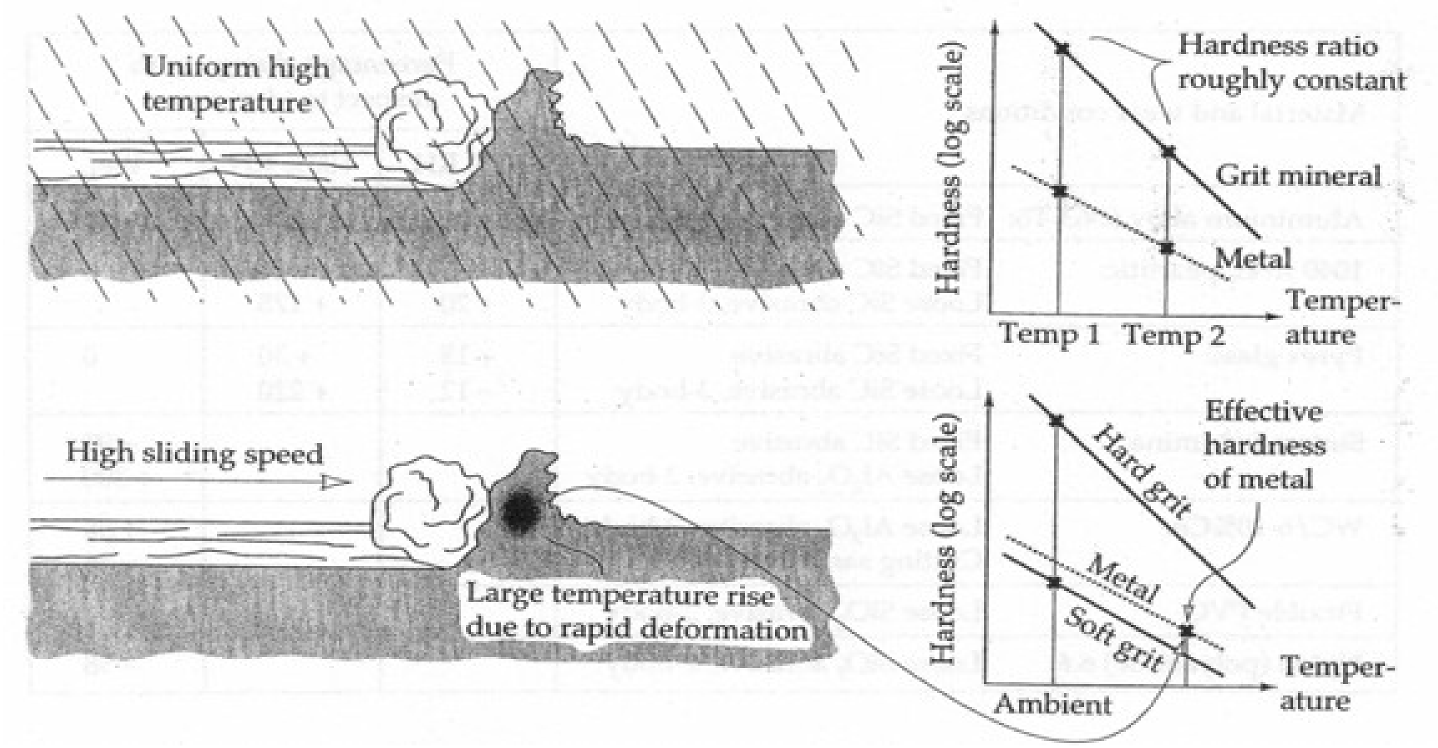




Severe abrasive wear when substrate hardness is less than 0.8 abrasive particle hardness

Effect of temperature

The hardness of materials decreases rapidly after 0.8xT_{melt}
The flash temperature at micro contacts.
Localized heating of softening of ploughed material



Effect of moisture:

- chemical reaction between moisture and substrate
- chemical reaction between moisture and lubricant
- corrosive property of the moisture

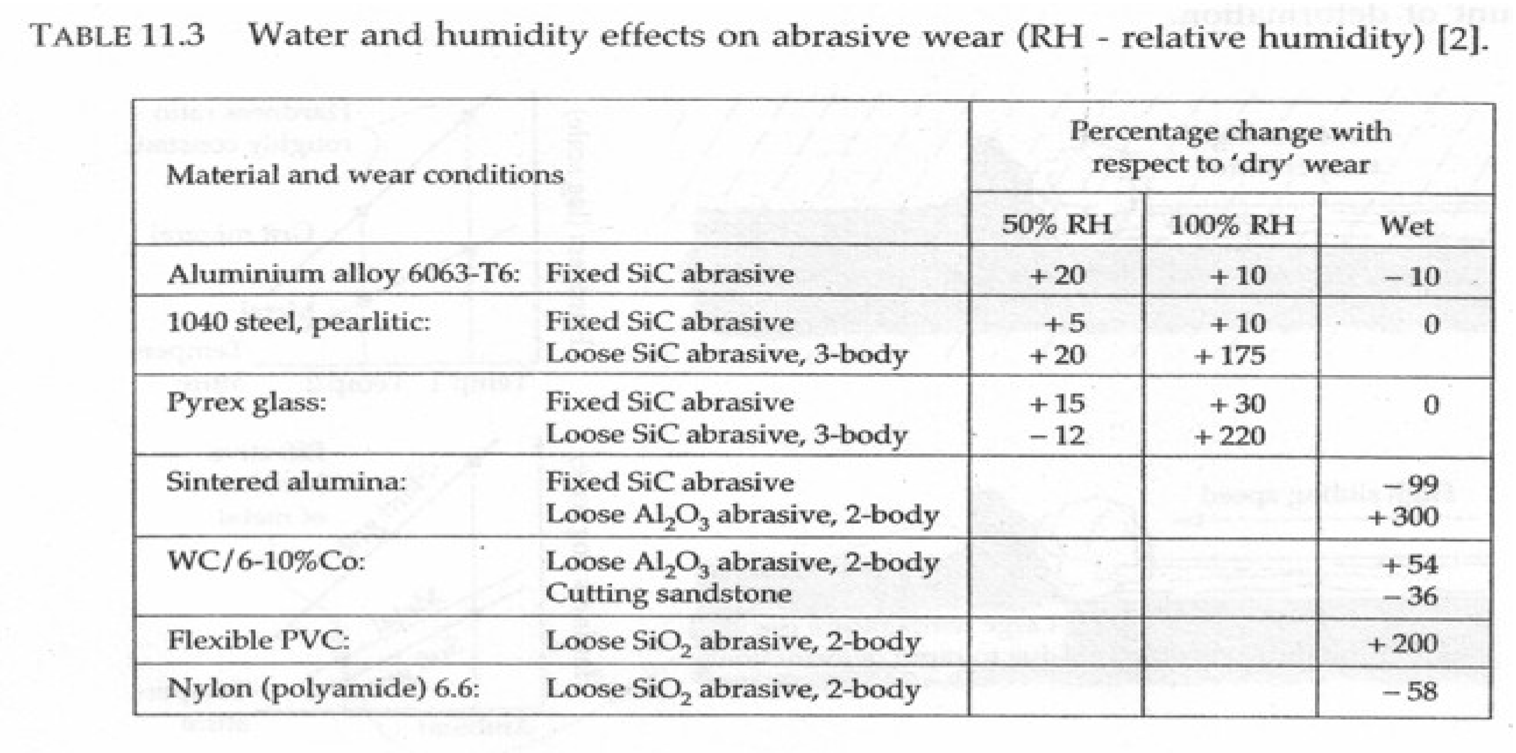
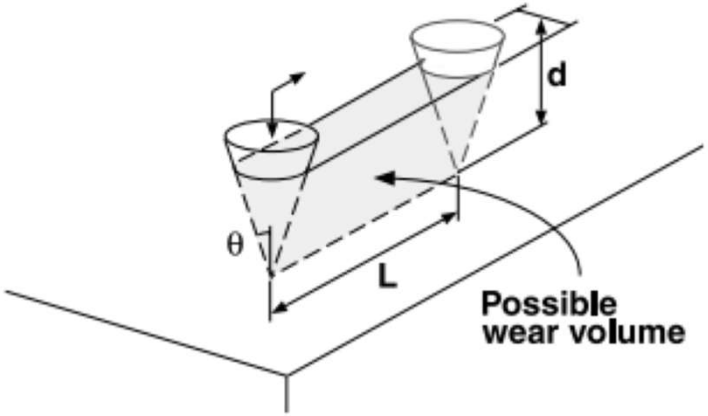


TABLE 11.3 Water and humidity effects on abrasive wear (RH - relative humidity) [2].

Material and wear conditions		Percentage change with respect to 'dry' wear		
		50% RH	100% RH	Wet
Aluminium alloy 6063-T6:	Fixed SiC abrasive	+20	+10	−10
1040 steel, pearlitic:	Fixed SiC abrasive	+5	+10	0
	Loose SiC abrasive, 3-body	+20	+175	
Pyrex glass:	Fixed SiC abrasive	+15	+30	0
	Loose SiC abrasive, 3-body	−12	+220	
Sintered alumina:	Fixed SiC abrasive			−99
	Loose Al_2O_3 abrasive, 2-body			+300
WC/6-10%Co:	Loose Al_2O_3 abrasive, 2-body			+54
	Cutting sandstone			−36
Flexible PVC:	Loose SiO_2 abrasive, 2-body			+200
Nylon (polyamide) 6.6:	Loose SiO_2 abrasive, 2-body			−58

Estimation of Abrasive wear Volume



$$V = \frac{2}{\pi \cdot \tan\theta} \cdot \frac{WL}{H_v}$$

Typical model of abrasive wear by a conical indentor.

Based on Sliding Velocity

V = K (WVs/3 σs)

Where

V = wear volume, Vs = sliding velocity

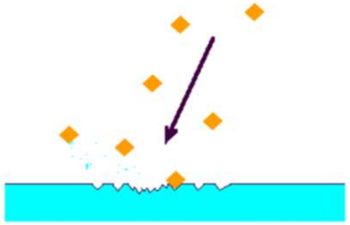
W = applied load, σs = surface strength

K = wear coefficient

Erosive Wear

- **Erosive Wear**

  Erosive wear can be described as an extremely short sliding motion and is executed within a short time interval. Erosive wear is caused by the impact of particles of solid or liquid against the surface of an object.



Types of erosion

Solid particle erosion
Surface wear by impingement of solid particles carried by a gas or fluid.

e.g. Wear of helicopter blade leading edges in dusty environments.

- **Liquid drop erosion**
  Surface wear by impingement of liquid drops.

e.g. Wear of centrifugal gas compressor blades by condensate droplets.

- **Cavitation erosion**
  Surface wear in a flowing liquid by the generation and implosive collapse of gas bubbles.

e.g. Fluid-handling machines as marine propellers, dam slipways, gates, and all other hydraulic turbines.

EROSIVE WEAR

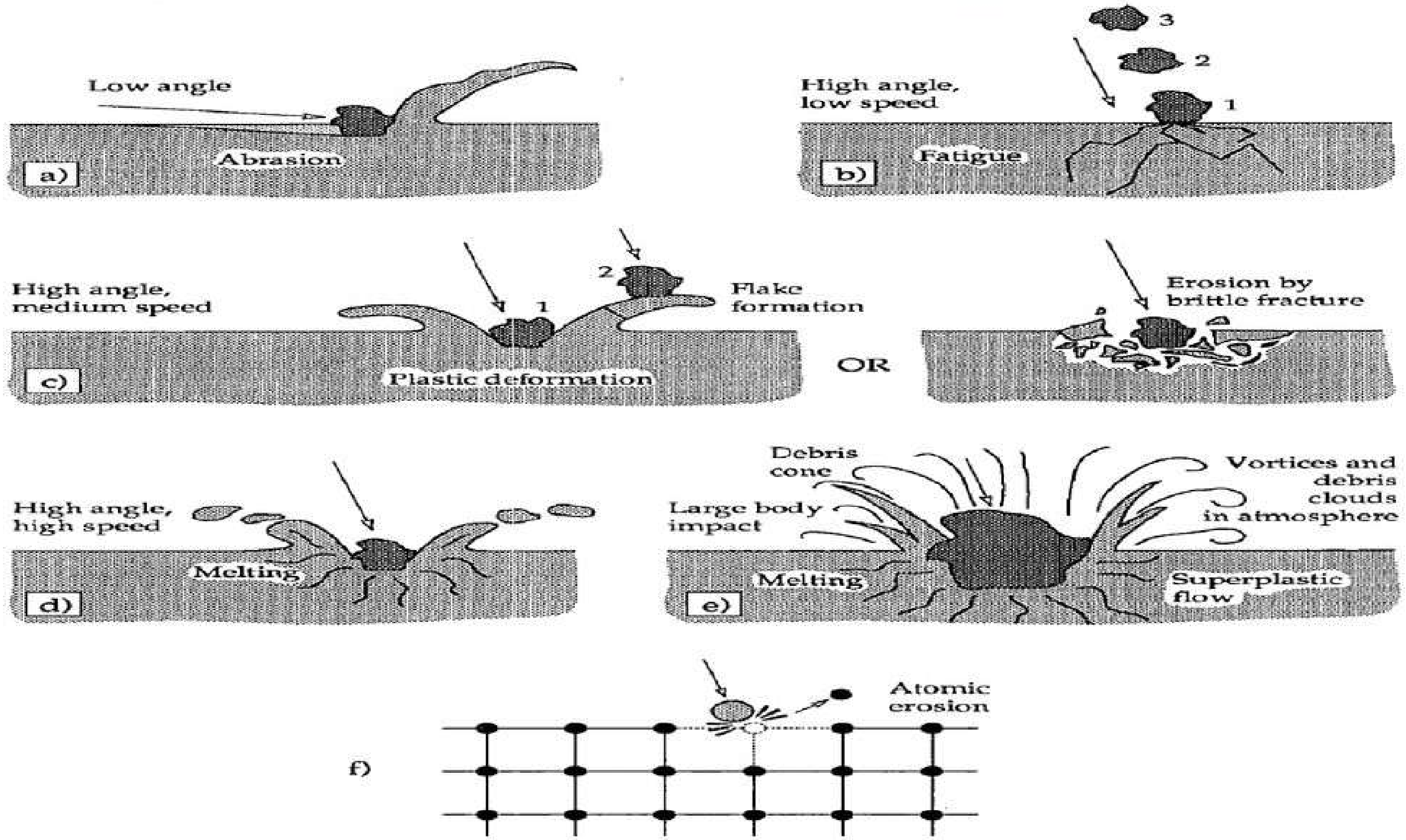
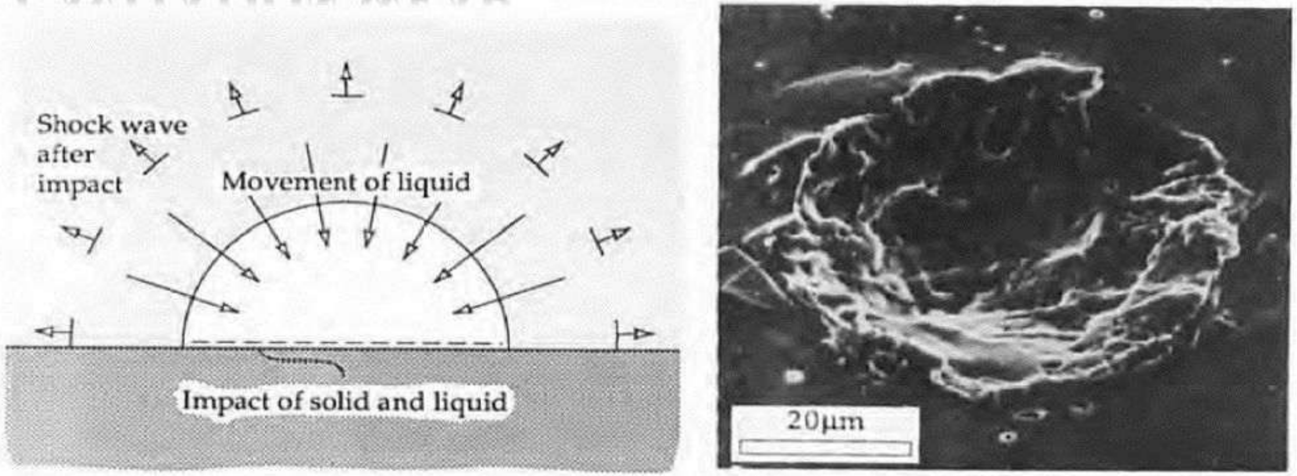


FIGURE Possible mechanisms of erosion; a) abrasion at low impact angles, b) surface fatigue during low speed, high impingement angle impact, c) brittle fracture or multiple plastic deformation during medium speed, large impingement angle impact, d) surface melting at high impact speeds, e) macroscopic erosion with secondary effects, f) crystal lattice degradation from impact by atoms.

CAVITATION WEAR



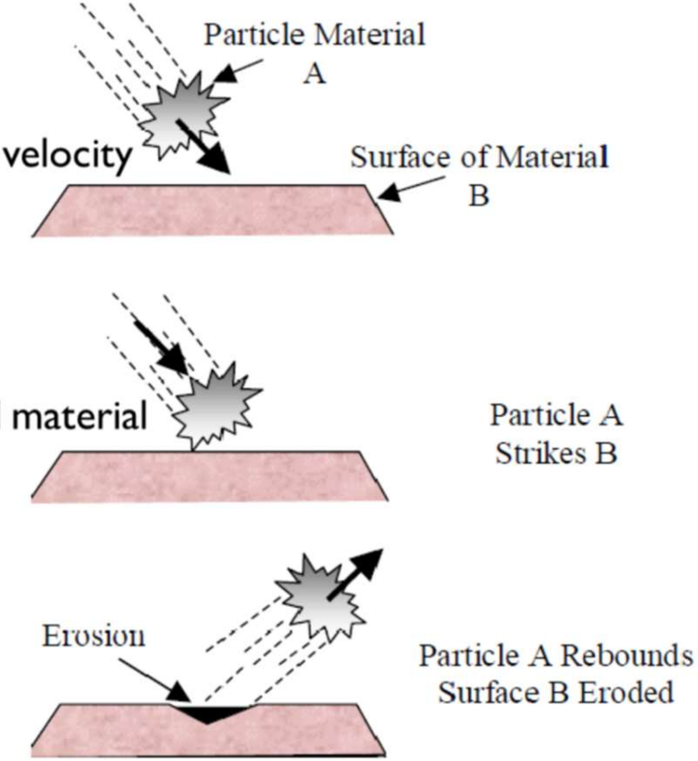
a) b)

FIGURE **Mechanism of cavitation wear; a) mechanism of bubble collapse, b) experimental evidence of damage by cavitation to a metallic (indium) surface**

Cyclic formation and collapse of bubbles on a solid surface.
Bubble formation is caused by the release of dissolved gas from the liquid, which has negative pressure.

Erosive wear

The impingement of solid particles, or small drops of liquid or gas on the solid surface cause wear what is known as erosion of materials and components.



Pressure generated due to change in velocity

$$P = \boldsymbol{\Delta} V\sqrt{E\boldsymbol{\rho}}$$

P = Impact pressure
E = Modulus of elasticity of impacted material
$\boldsymbol{\rho}$ = Density of the fluid
V = Velocity

Advantages

- Cutting, drilling and polishing of brittle material

Erosive wear rate(V_e) is function of :

1. Particles velocity (K.E.)

2. Impact angle and

3. Size of abrasive.

$V_e = K.A(\alpha).(\text{particle\_vel})^n.(\text{particle\_size})^3.$

Fatigue Wear

Fatigue wear is a type of wear in which the surface damage of the material takes place due to strain induced on the surface for a particular number of cycles to a certain critical limit.

The wear occurring due to surface fatigue is termed fatigue wear. Surface fatigue is caused due to the repeated stressing—and unstressing of the contacts. Cracks develop due to the accumulation of irreversible changes.

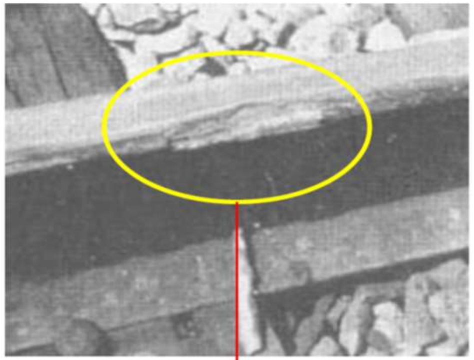
Fatigue Wear

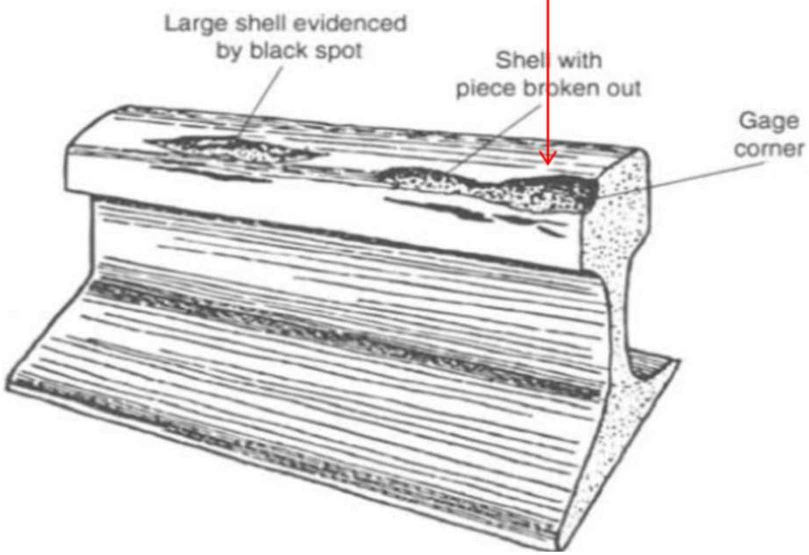
Surface fatigue

- Two surfaces contacting to each other under pure rolling, or rolling with a small amount of sliding in contact

Contact fatigue

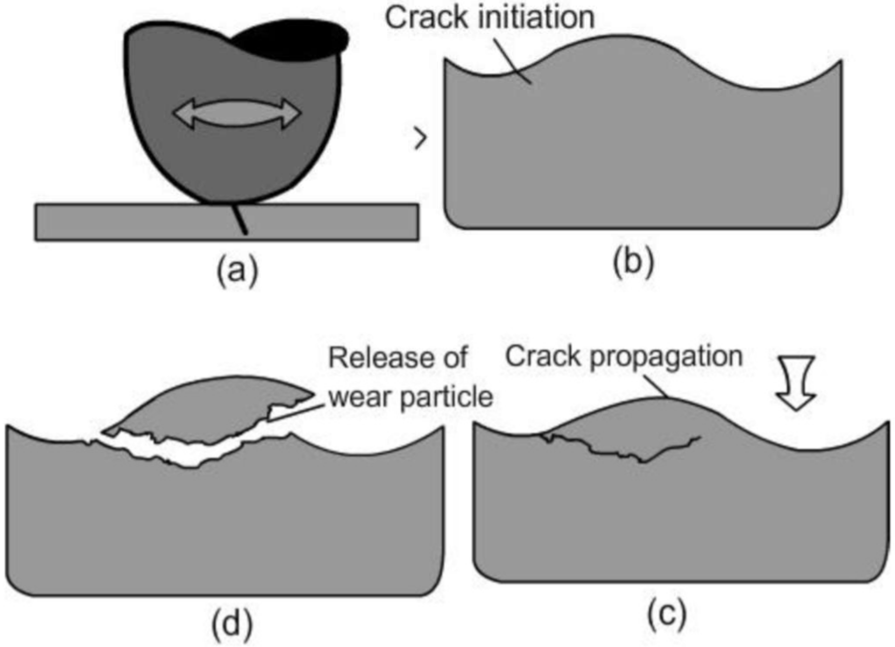
- As one element rolls many times over the other element
- Maximum shear stress is higher than fatigue limit

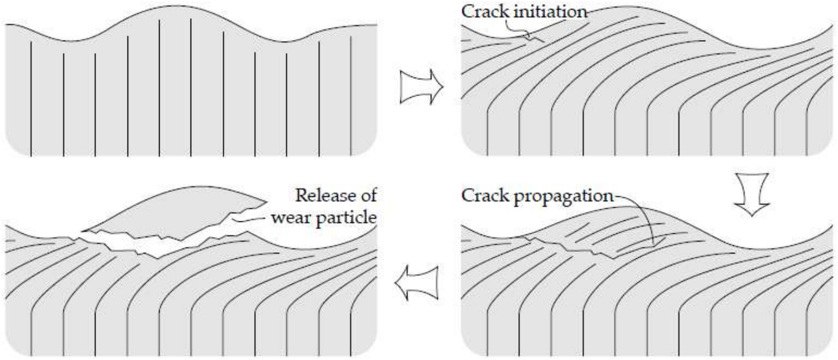




Fatigue wear steps

Mechanism of fatigue wear.



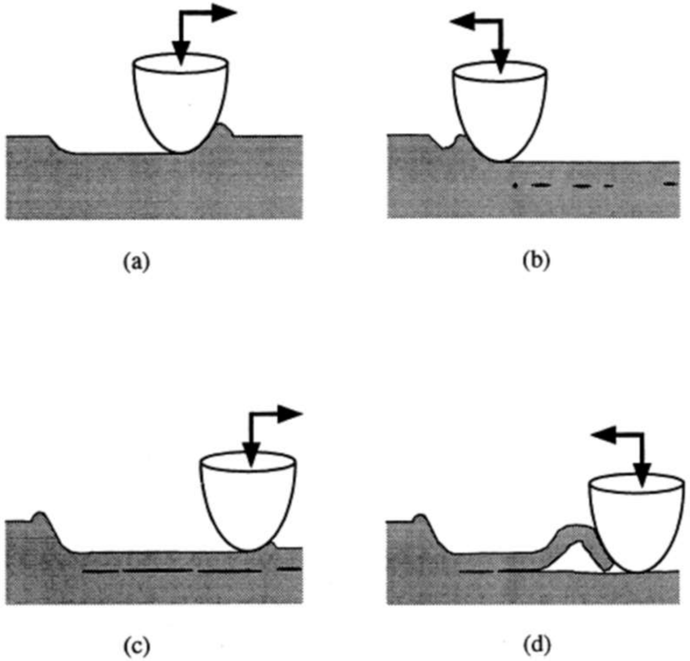


Delamination wear

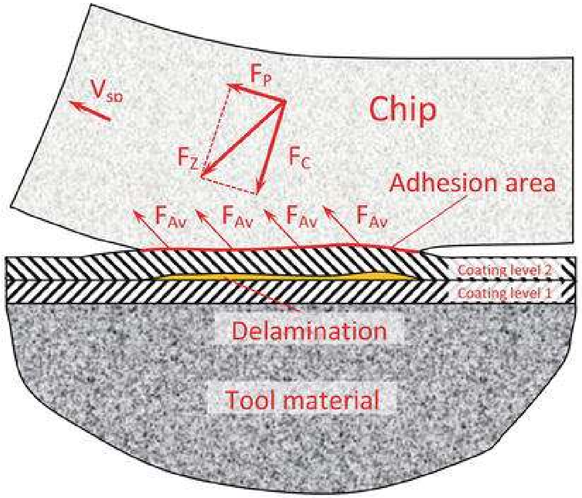
A wear process where a material loss from the surface by forces of another surface acting on it in a sliding motion in the form of thin sheets.

Mechanisms of delamination wear

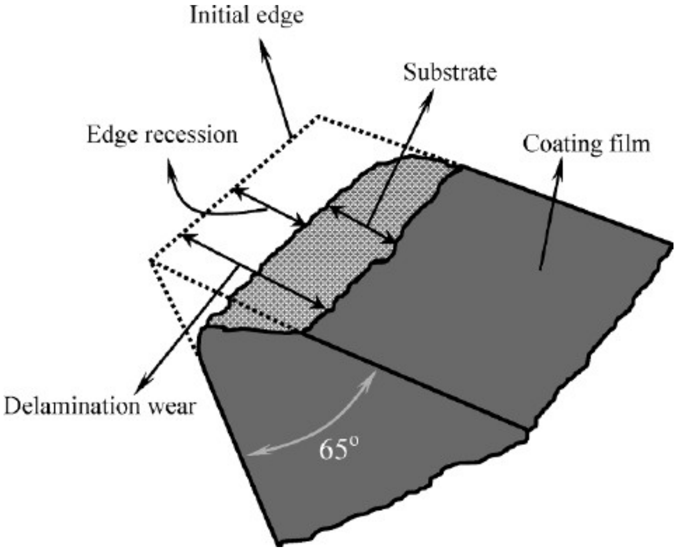
- Plastic deformation of the surface
- Cracks are nucleated below the surface
- Crack propagation from these nucleated cracks and joining with neighbouring one
- After separation from the surface, laminates form wear debris



Delamination Wear



F_{Av} – avulsion force (сила отрыва)
F_P - thrust force
F_C - cutting force
F_Z - The resultant force



Corrosive wear

Corrosive wear is defined as “a wear process in which chemical or electrochemical reaction with the environment predominates” (OECD, 1969).
In many cases, the mechanochemical mechanism combines chemical reaction and mechanical action enhances the corrosive wear.

Corrosive Wear also known as oxidation or chemical wear, this type of wear is caused by chemical and electrochemical reactions between the surface and the environment. The fine corrosive products on the surface constitute the wear particles in corrosive wear.

Chemical wear

Environmental conditions produce a reaction product on one or both of rubbing surface and this chemical product is subsequently removed by the rubbing action.

Stages of corrosive wear :

- Sliding surfaces chemically interact with environment (humid/industrial vapor/acid)

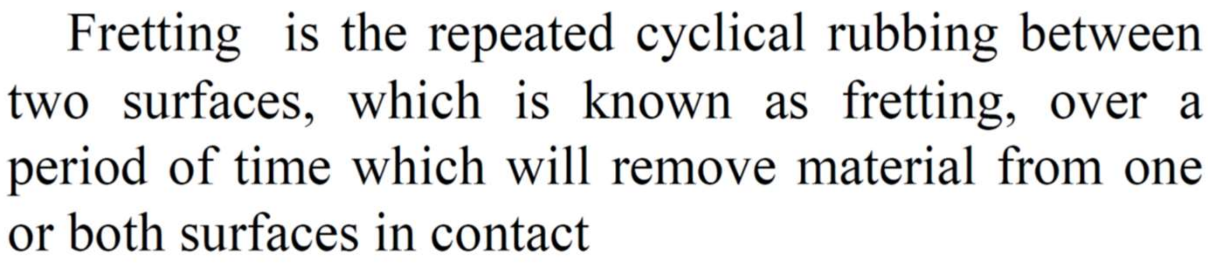
- A reaction product (like oxide, chlorides, copper sulphide)

- Wearing away of reaction product film.

Corrosive wear

- Chemical reaction + Mechanical action = Corrosive wear
- The fundamental cause of Corrosive wear is a chemical reaction between the material and a corroding medium which can be either a chemical reagent, reactive lubricant or even air. Understanding the mechanisms of corrosive is important to reduce this kind of wear.
- Let us consider a jaw coupling used for connecting shaft and motor, as shown in Fig. This coupling is corroded, due to moist environment and its outer dimensions have increased. If we rub this coupling with fingers, brown colour debris will get detached from the coupling surface. In other words, after chemical reactions, mechanical action is essential to initiate corrosive wear.

Fretting wear



Fretting is the repeated cyclical rubbing between two surfaces, which is known as fretting, over a period of time which will remove material from one or both surfaces in contact

Fretting wear is a type of fatigue wear caused by cycling sliding or oscillating with small amplitude of two surfaces across each other due to production of friction force alternating compression–tension stresses.

Fretting wear is a specific type of wear that occurs at the contact surfaces of two materials subjected to small, repetitive relative motion. This phenomenon typically arises under conditions of oscillatory motion, such as vibrations or micro-sliding, where the displacement amplitude is often very small (typically in the micrometer range).

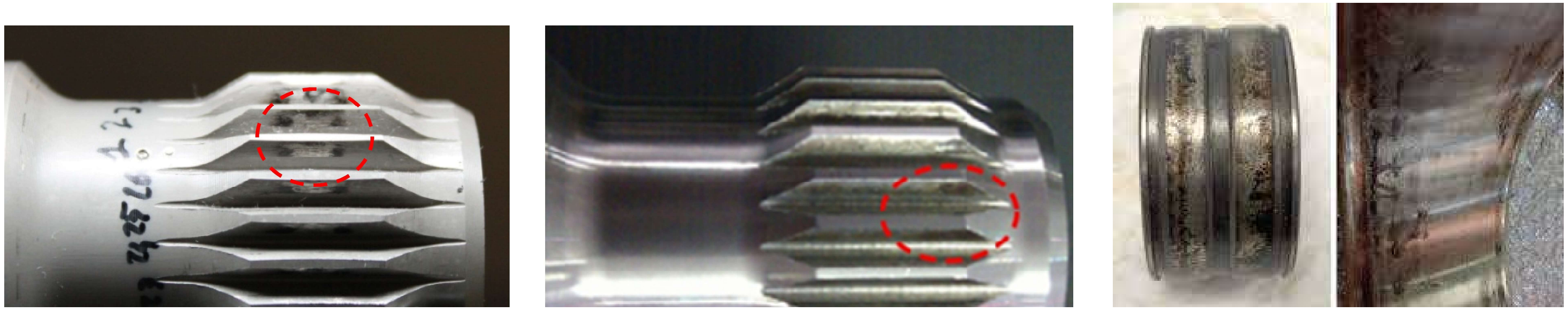
Understanding Fretting Wear

Microscopic Motion

Fretting wear occurs when two surfaces in contact experience relative motion, even if it's very small. This can happen due to vibrations, thermal expansion, or other factors.

Degradation

The repeated contact between surfaces under pressure causes microscopic damage, leading to the formation of debris and surface degradation. This process is known as fretting wear.



wear resistance measurement

Unlike many other engineering properties, wear resistance does not have well standardized tests for its measurement.

The main reason for this is the complexity of wear, which tends to make the tests highly specific and make translation of wear test data into valid predictions of service performance very uncertain

Abrasion Test according to

ISO 9352

ASTM G65 (Dry Sand) test

ASTM D 968-93 (inorganic material)

ASTM D1044, D3389, D4060 (Taber Abrasion: plastic's resistance to abrasion)

wear resistance measurement

Weight loss

Volume loss

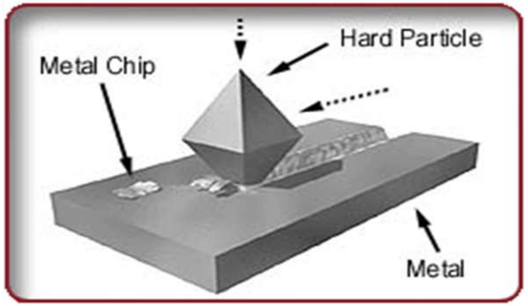
The volume loss gives a truer picture than weight loss, particularly when comparing the wear resistance properties of materials with large differences in density.

Particle Volume

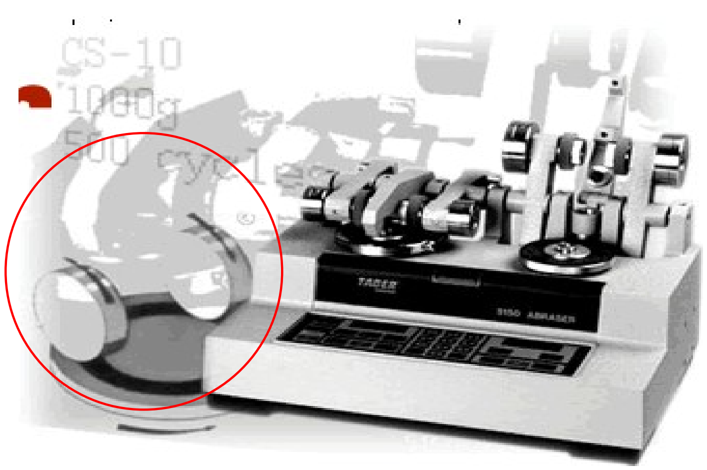
The abrasive wear theory expresses the total volume of wear particles generated V, per unit of sliding length L

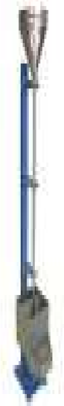
Abrasive Wear Test

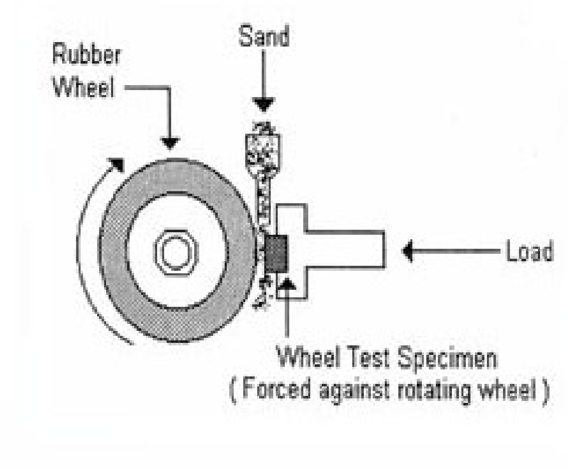
Depending on the material being examined, different wear test configurations can be used.



Taber Abrasion







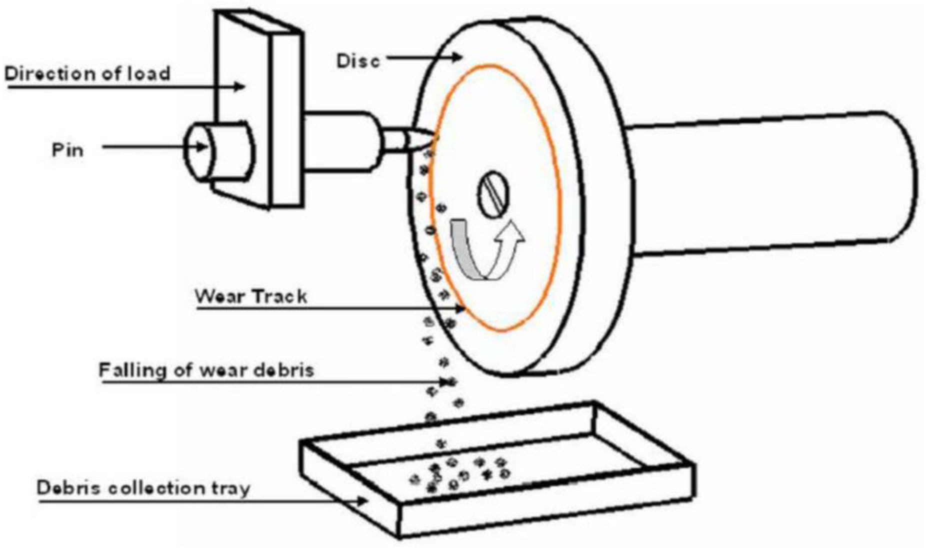
TRIBOLOGICAL INSTRUMENTS

TRIBOMETER

- Measures tribological quantities, such as coefficient of friction, friction force, and wear volume.
- Invented By- Dutch scientist Musschenbroek.

TRIBOMETER

EXPERIMENTAL SET-UP



Schematic diagram of loading configuration of Pin-on-Disc.

Testing Methods for Abrasive Wear

Group 1: The specimen pin slides over the fixed abrasive particles. This causes two body abrasive wear.

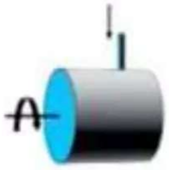
1. Pin on abrasive disc
2. Pin on abrasive plate
3. Pin on abrasive drum

Group 2: Loose abrasive particles are supplied as dry powder or mixed with liquid to form a slurry.

1. Rubber wheel abrasion test
2. Micro scale abrasion test

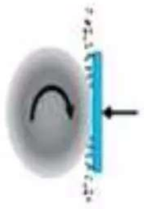
Pin on abrasive disc

Pin on abrasive plate



Pin on abrasive drum

Rubber wheel abrasion test



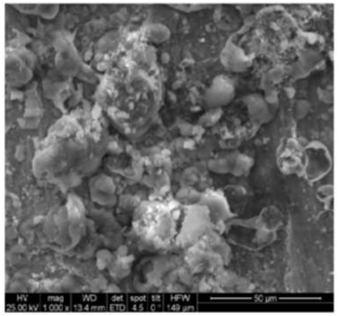
Micro scale abrasion test or ball cratering

WEAR RATE

Wear rate of Ti-6Al-4V under ambient condition at 1kg,4kg and 8kg

SEM ANALYSIS

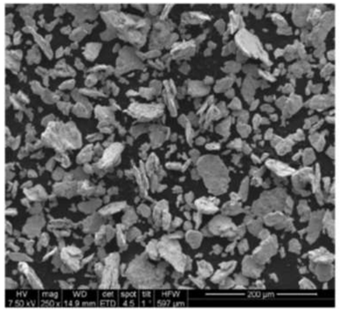
AT AMBIENT CONDITION

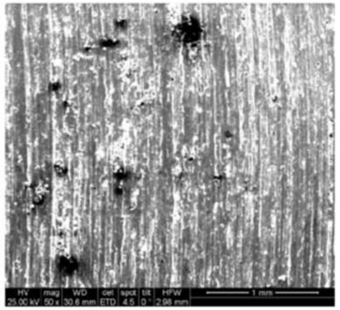


Speed 0.1m/sec at 1kg

Source :Materials engg,IISc,Bangalore

Abrasive wear





Speed 0.8m/sec at 1kg

Wear Prevention

- Common approaches to minimizing wear are:

-Lubricants (Use oil free of abrasive particles, Use more viscous oil, frequent oil changes)
-Recognizing the type of wear
-Making changes in the operation
-Making changes in the design (Wear resistance materials, Surface-hardening treatments).

- Surface-hardening treatments for reducing wear include:

- case carburizing commonly used in engine crankshafts,
- ion implantation used in surgical instruments
- hard-faced ceramic coatings used in turbine blades and fiber guides in the textile industry .

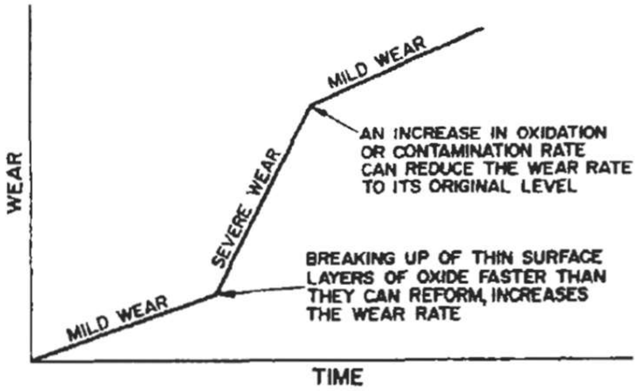
IDENTIFICATION OF WEAR MECHANISM

❑ **Examination of the wear debris (collected)**

- large lumps imply- adhesive wear
- fine particles- oxidative wear
- chip like particles-abrasive wear
- flake like particles-delamination wear

❑ **Examination of the worn surfaces:**

- Heavy tearing implies - adhesive wear
- Scratches imply -abrasive wear
- burnishing indicates –non adhesive wear



AN INCREASE IN OXIDATION OR CONTAMINATION RATE CAN REDUCE THE WEAR RATE TO ITS ORIGINAL LEVEL

BREAKING UP OF THIN SURFACE LAYERS OF OXIDE FASTER THAN THEY CAN REFORM, INCREASES THE WEAR RATE

Wear resistance materials

1- Austenite manganese steel
2- Hardened and tempered alloy steel
3- Abrasion resistant cast-iron
4- High chromium steel
5- Based (nickel ,iron or cobalt alloyed) matrix containing tungsten or titanium carbides particles.

Using such a combination, both high degrees of hardness and toughness can be obtained

Wear resistance of ferrous alloys

Requirement: combination of hardness and toughness

Usually, austenite and bainite phase are better than martensite, by fatigue mechanism

Low alloy steels:

Hypo-eutectoid: Bainite > Tempered martensite > ferrite/pearlite

Hyper-eutectoid: Annealed with presence of carbides is best

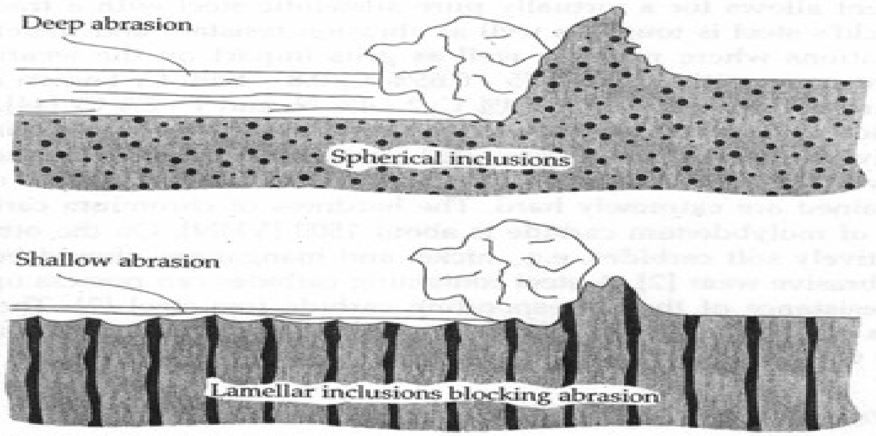


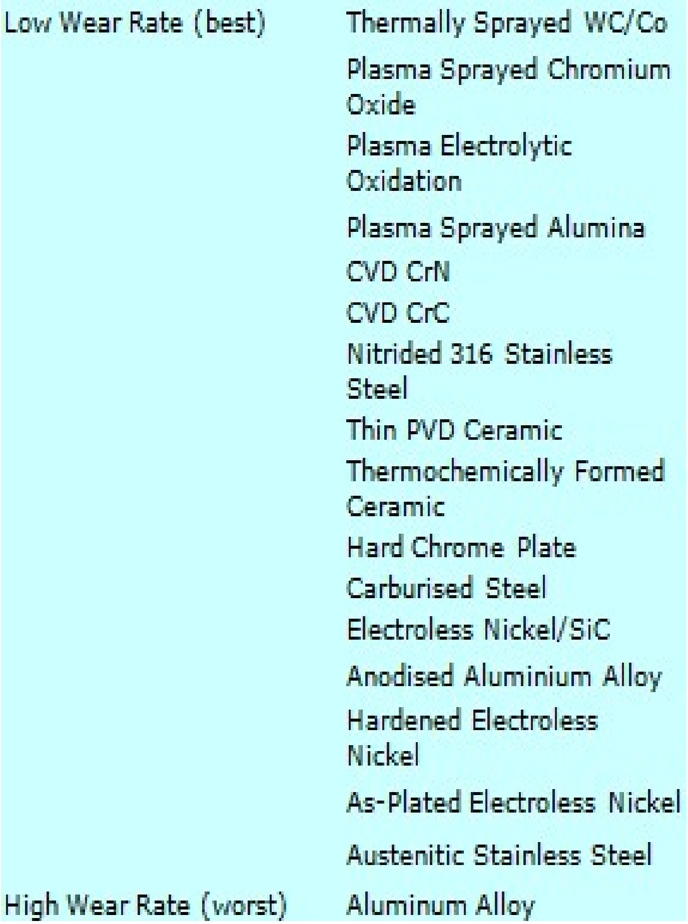
FIGURE 11.19 Influence of carbide inclusion morphology on the abrasion process.

Coatings methods

These coatings are traditionally applied using a variety of methods such as:

- weld overlays (MIG, plasma transfer arc, laser-cladding)
- thermal spray processes (high velocity oxygen fuel, plasma spray)
- Brazing

Typical Low Stress Abrasive Wear Rankings



Low Wear Rate (best)	Thermally Sprayed WC/Co
	Plasma Sprayed Chromium Oxide
	Plasma Electrolytic Oxidation
	Plasma Sprayed Alumina
	CVD CrN
	CVD CrC
	Nitrided 316 Stainless Steel
	Thin PVD Ceramic
	Thermochemically Formed Ceramic
	Hard Chrome Plate
	Carburised Steel
	Electroless Nickel/SiC
	Anodised Aluminium Alloy
	Hardened Electroless Nickel
	As-Plated Electroless Nickel
	Austenitic Stainless Steel
High Wear Rate (worst)	Aluminum Alloy

Typical high Stress Abrasive Wear Rankings

Low Wear Rate (best)	Thermally Sprayed WC/Co
	CVD CrC
	CVD CrN
	Salt Bath Carbide Diffusion Coating
	Thick PVD Ceramic Coating
	Hard Chrome Plate
	Sprayed and HIPPED CrC/Ni/Cr
	Plasma Sprayed Alumina
	Electroless Nickel/SiC
	Boronised Stainless Steel
	Plasma Sprayed Chromium Oxide
	Spray Fused Ni/Cr/CrC
	Carburised Steel
	Induction Hardened Steel
	Thermo chemically Formed Ceramic
	Nitride 316 Stainless Steel
	Hardened Electroless Nickel
	As-Plated Electroless Nickel
	Thin PVD Ceramic
High Wear Rate (worst)	Anodized Aluminum Alloy

Lubricant

Lubrication

Lubrication is the process or technique employed to reduce wear of one or both surfaces in close proximity, and moving relative to each another, by interposing a substance called lubricant between the surfaces to carry or to help carry the load (pressure generated) between the opposing surfaces.

Role of lubricants

1. Change surface energy (monolayer)
2. Reduce metal to metal contact through wetting
3. Prevent particle agglomeration through wetting

The Function of Lubricants

Protection

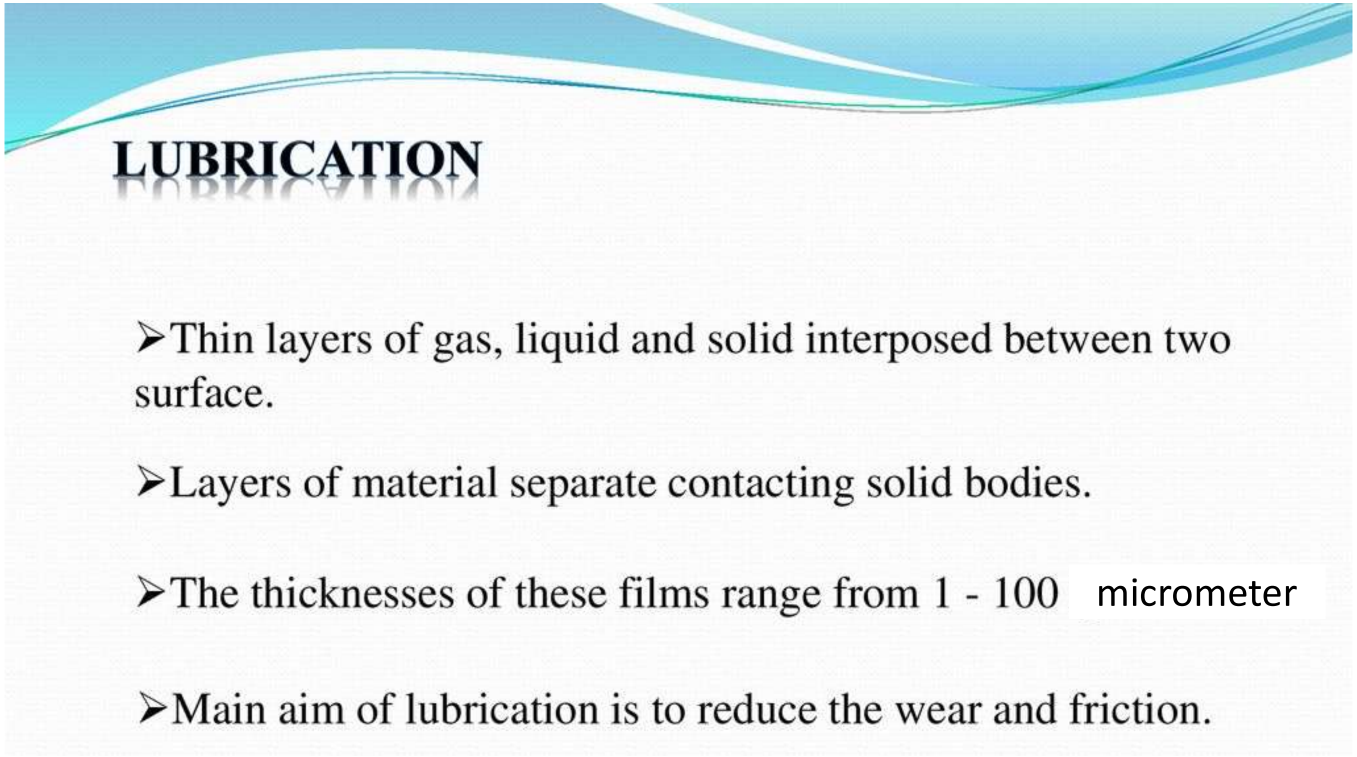
Creates a barrier between surfaces to prevent direct contact.

Heat Dissipation

Helps transfer heat away from critical components.

Cleaning

Carries away debris and contaminants from moving parts.



LUBRICATION

- Thin layers of gas, liquid and solid interposed between two surface.
- Layers of material separate contacting solid bodies.
- The thicknesses of these films range from 1 - 100 micrometer
- Main aim of lubrication is to reduce the wear and friction.

Types of Lubricants:

Liquid Lubricants: These are the most common type, including oils and greases.

Solid Lubricants: Materials like graphite, molybdenum disulfide, and PTFE can provide lubrication in extreme conditions or where liquid lubricants are not suitable.

Gas Lubricants: Gases like air or nitrogen can be used as lubricants in specific applications, such as high-speed bearings

Lubricant Composition and Properties

Base Oils

Mineral, synthetic, or vegetable oils form the foundation.

Additives

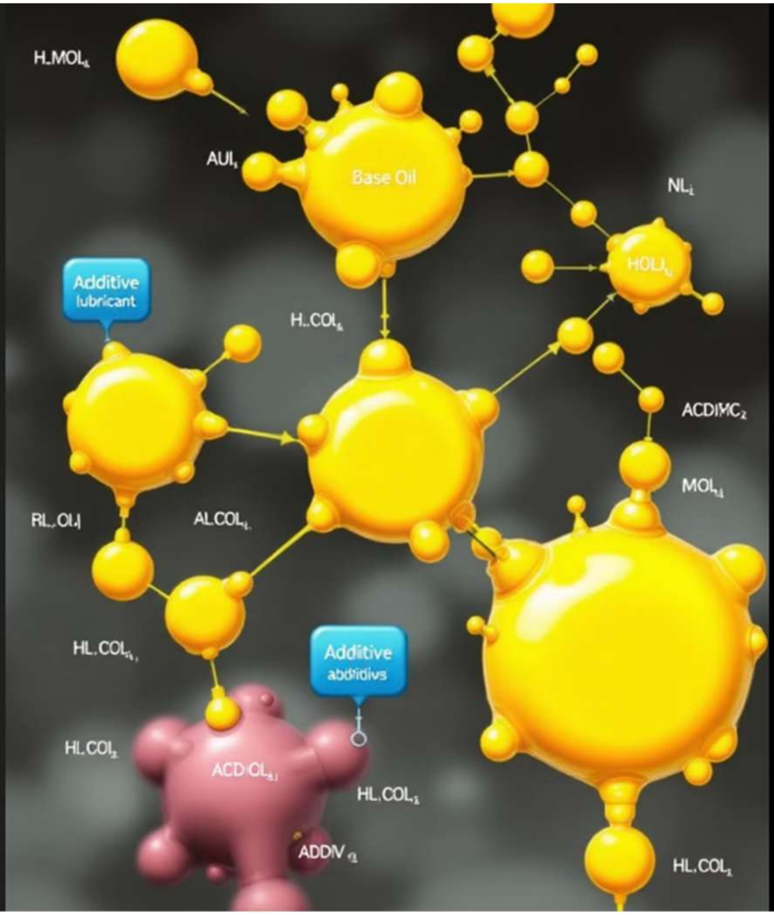
Enhance performance with anti-wear, anti-oxidation, and other properties.

Viscosity

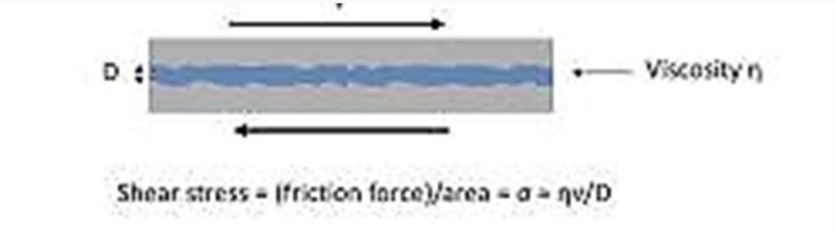
Measures a lubricant's resistance to flow at different temperatures.

Stability

Ability to maintain properties under various operating conditions.

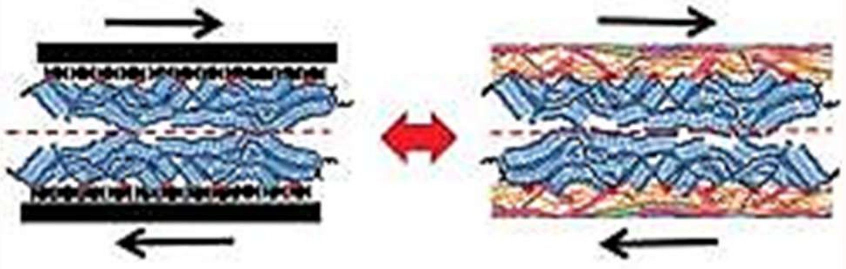


Fluid Film Lubrication:
When a sufficient amount of lubricant is present, it forms a film between two moving surfaces, separating them and significantly reducing friction. This is common in well-lubricated engines and bearings.



(A) Fluid film lubrication

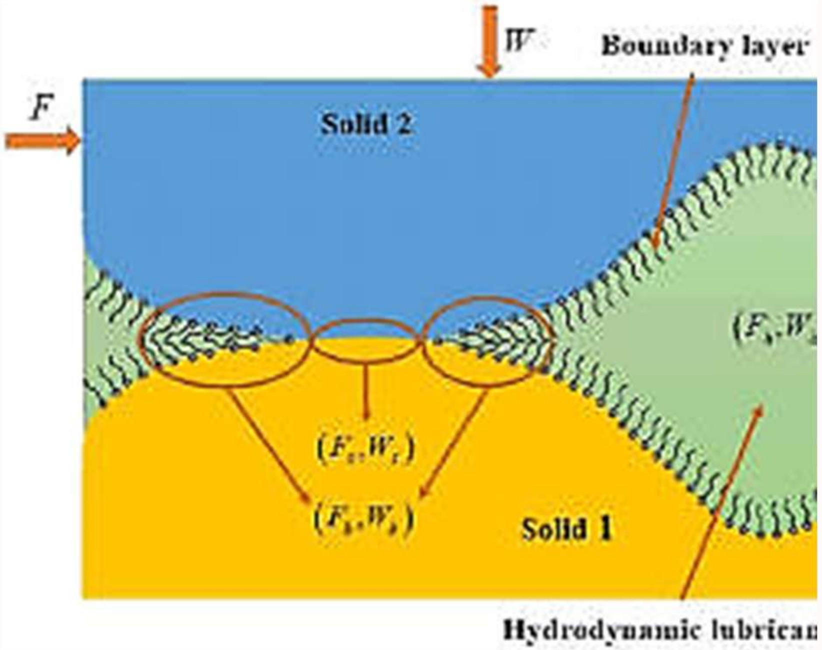
Boundary Lubrication:
In situations with high loads or low lubricant supply, the lubricant molecules adhere to the surfaces, forming a thin layer that prevents direct metal-to-metal contact. This reduces friction, but it's not as effective as fluid film lubrication.



(B) Boundary lubrication

Mixed Lubrication:

This is a combination of fluid film and boundary lubrication, where both mechanisms contribute to friction reduction. It occurs in many real-world applications.



Lubricants and Lubrication Regimes

Hydrodynamic

Surfaces are fully separated by a thick lubricant film, minimizing direct contact and friction.

Boundary

Surfaces are in direct contact, with a thin thin lubricant film providing only partial partial separation.

Mixed

A combination of hydrodynamic and and boundary lubrication, with some some direct surface contact.

Solid Lubrication

The use of solid materials, such as graphite or PTFE, to reduce friction and and wear.

Lubrication Regimes

1 Boundary Lubrication

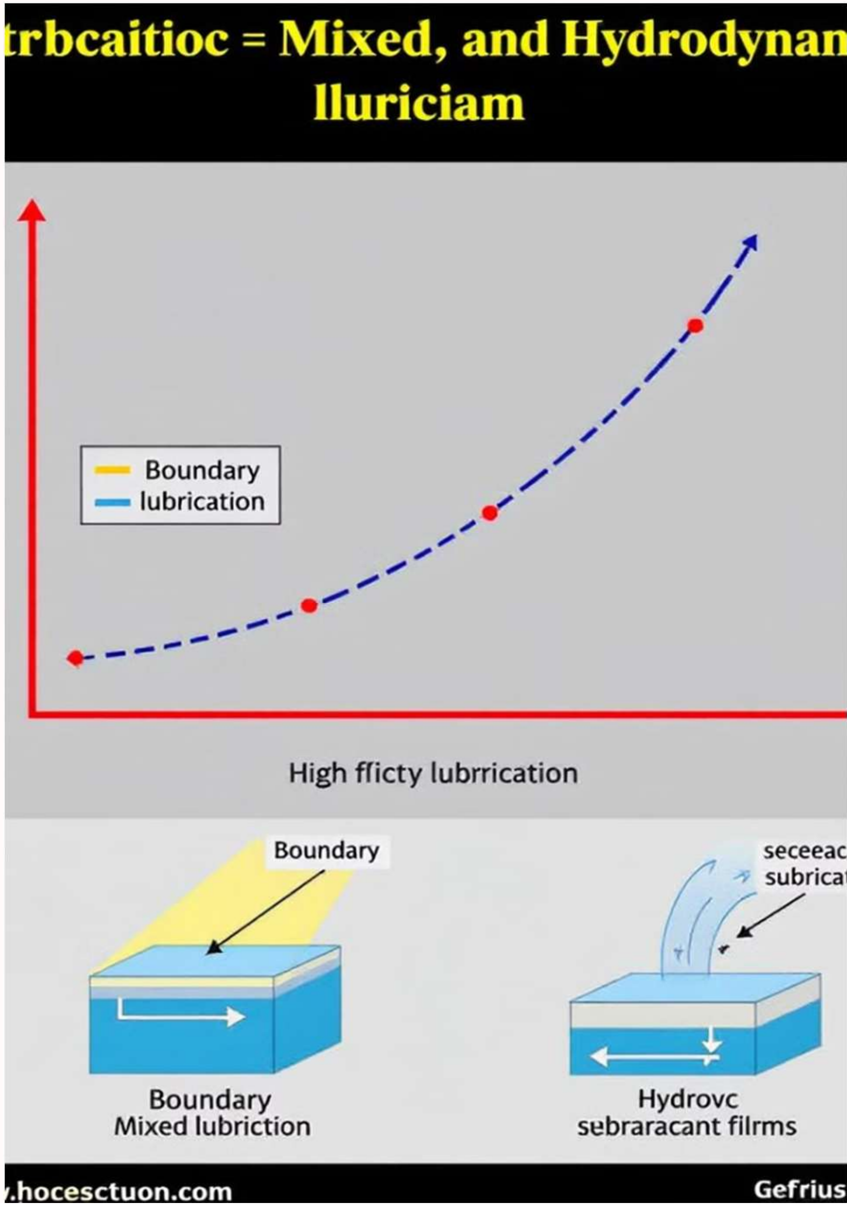
Thin film separates surfaces, high friction and wear.

2 Mixed Lubrication

Partial separation, moderate friction and wear.

3 Hydrodynamic Lubrication

Complete separation by fluid film, low friction and wear.



TYPES OF LUBRICATIONS

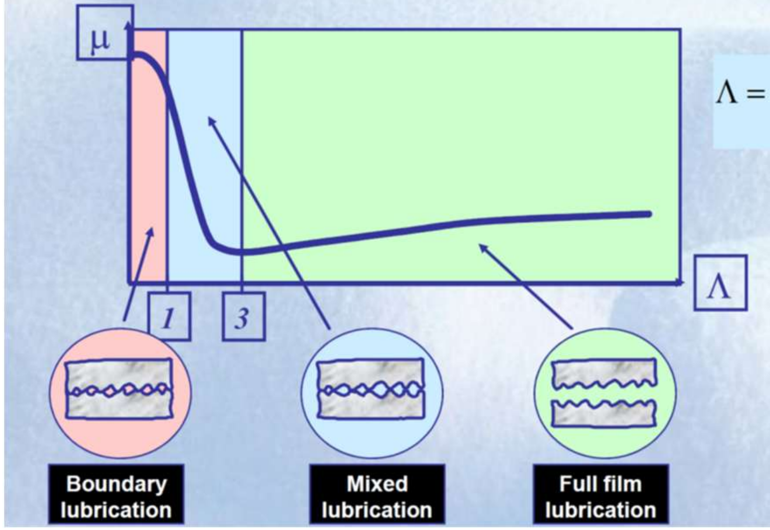
- **Hydrodynamic lubrication-** Analysis of Gaseous or liquid films is usually termed
- **Solid lubrication-** Lubrication by solids is termed, Ex. Graphite
- **Elastohydrodynamic lubrication-** Physical interaction between the contacting Bodies and the liquid lubricant.
- **Hydrostatic lubrication**- Complete separation of sliding surfaces with negligible wear and very low friction. Applied to aerostatic and hybrid bearings.

Regimes of Lubrication

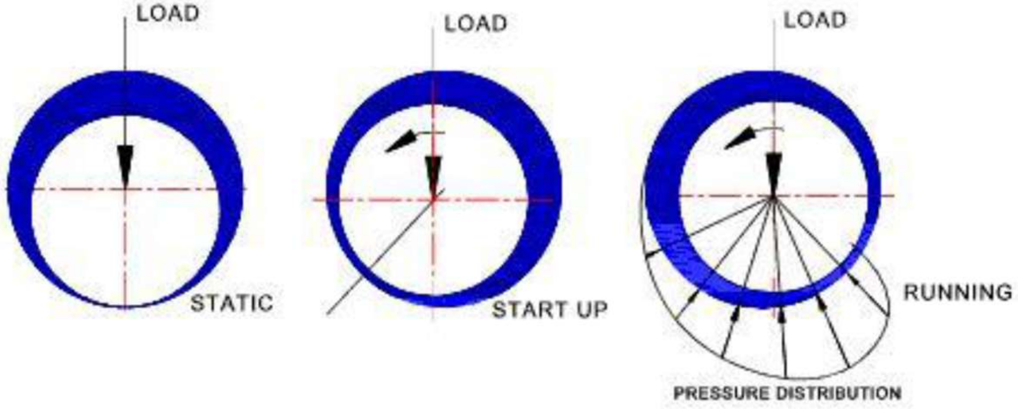
As the load increases on the contacting surfaces three distinct situations can be observed with respect to the mode of lubrication, which are called regimes of lubrication:

- **Fluid film lubrication or boundary lubrication**
- **Hydrostatic lubrication**
- **Hydrodynamic lubrication (thick film)**
- **Extreme pressure lubrication**

Lubricated Friction Classification



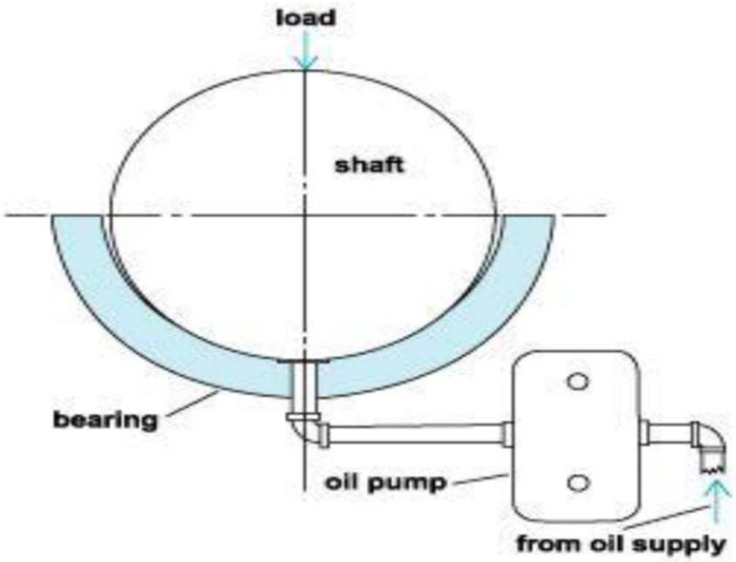
$$\Lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$



- Hydrodynamic lubrication depends on the relative speed between the surfaces, oil viscosity, load, and clearance between the moving or sliding surfaces.
- In hydrodynamic lubrication the lube oil film thickness is greater than outlet, pressure at the inlet increases quickly, remains fairly steady having a maximum value a little to the outside of the bearing center line, and then decreases quickly to zero at the outlet.

Hydrostatic Lubrication

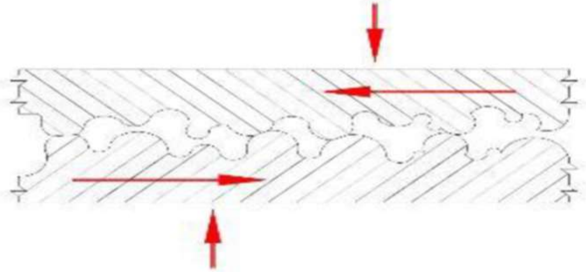
- Hydrostatic lubrication is essentially a form of hydrodynamic lubrication in which the metal surfaces are separated by a complete film of oil, but instead of being self-generated, the separating pressure is supplied by an external oil pump. Hydrostatic lubrication depends on the inlet pressure of lube oil and clearance between the metal surfaces, whereas in hydrodynamic lubrication it depends on the relative speed between the surfaces, oil viscosity, load on the surfaces, and clearance between the moving surfaces.
- Example: the cross head pin bearing or gudgeon pin bearing in two stroke engines employs this hydrostatic lubrication mechanism. In the cross head bearing, the load is very high and the motion is not continuous as the bearing oscillation is fairly short



Hydrostatic Lubrication

Boundary Lubrication or Thin Film Lubrication

- Boundary lubrication exists when the operating condition are such that it is not possible to establish a full fluid condition, particularly at low relative speeds between the moving or sliding surfaces.
- The oil film thickness may be reduced to such a degree that metal to metal contact occurs between the moving surfaces. The oil film thickness is so small that oiliness becomes predominant for boundary lubrication.
- Boundary lubrication happens when
  - A shaft starts moving from rest.
  - The speed is very low.



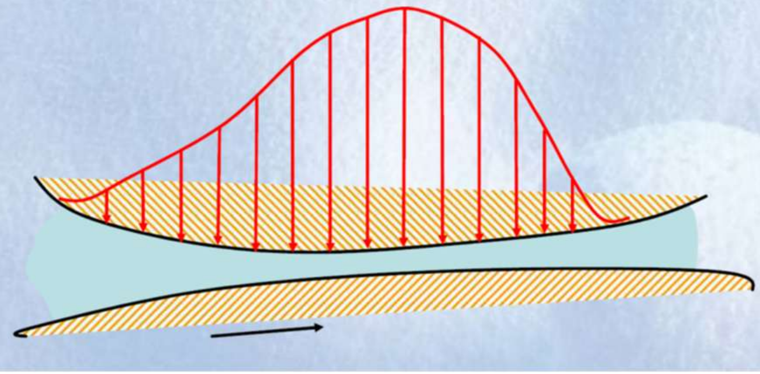
Boundary Lubrication

Extreme pressure lubrication

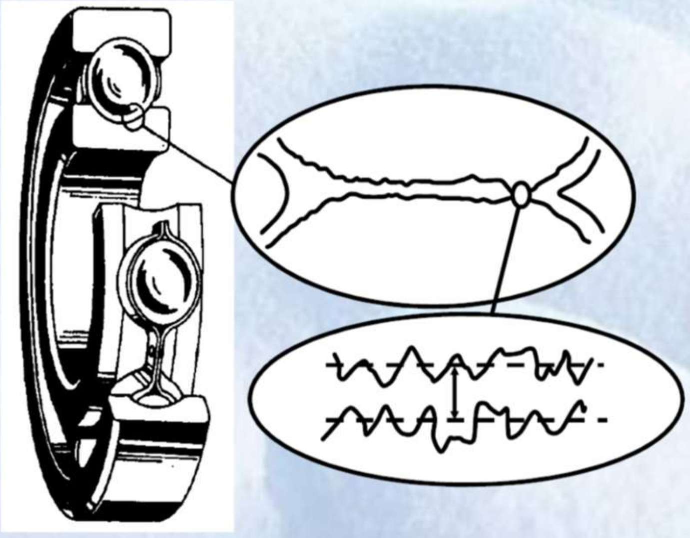
- When the moving or sliding surfaces are under very high pressure and speed, a high local temperature is attained. Under such condition, liquid lubricant fails to stick to the moving parts and may decompose and even vaporize. To meet this extreme pressure condition, special additives are added to the minerals oils. These are called “extreme pressure lubrication.” These additives form on the metal surfaces more durable films capable of withstanding high loads and high temperature. Additives are organic compounds like chlorine (as in chlorinated esters), sulphur (as in sulphurized oils), and phosphorus (as in tricresyl phosphate).

Full film lubrication: The lubricant film separates the surfaces

A hydrodynamic pressure is formed due to the converging gap → surface separation!



EHL - What is that?



Elastohydrodynamic lubrication (EHL)

Non-conformal surfaces → small contact region

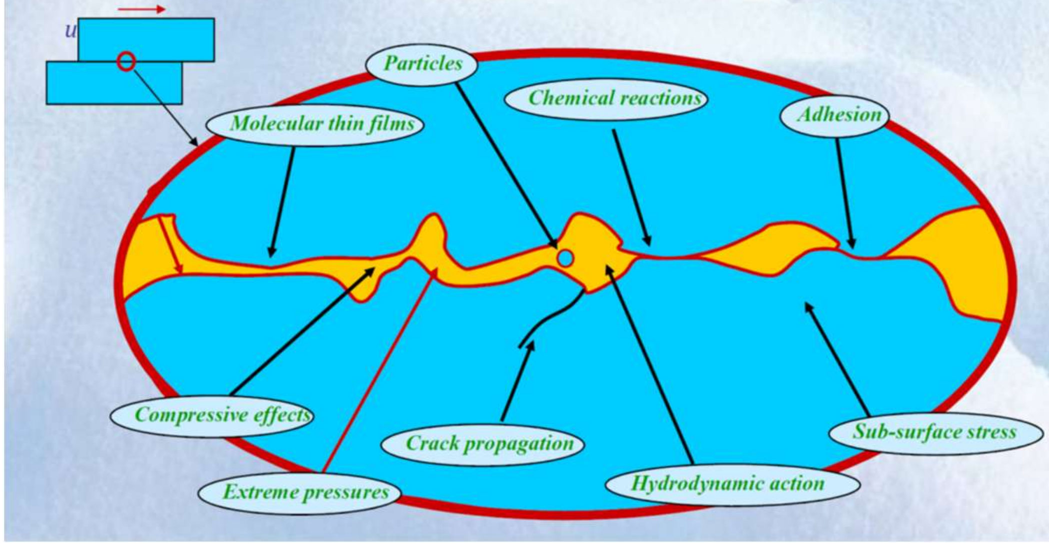
High contact pressures, 1-3 GPa (1000-3000 N/mm^2)

The surfaces are deformed

Thin lubricant films <1μm

Example: the ball bearing

Lubricated Contacting Surfaces



Particles

Chemical reactions

Adhesion

Molecular thin films

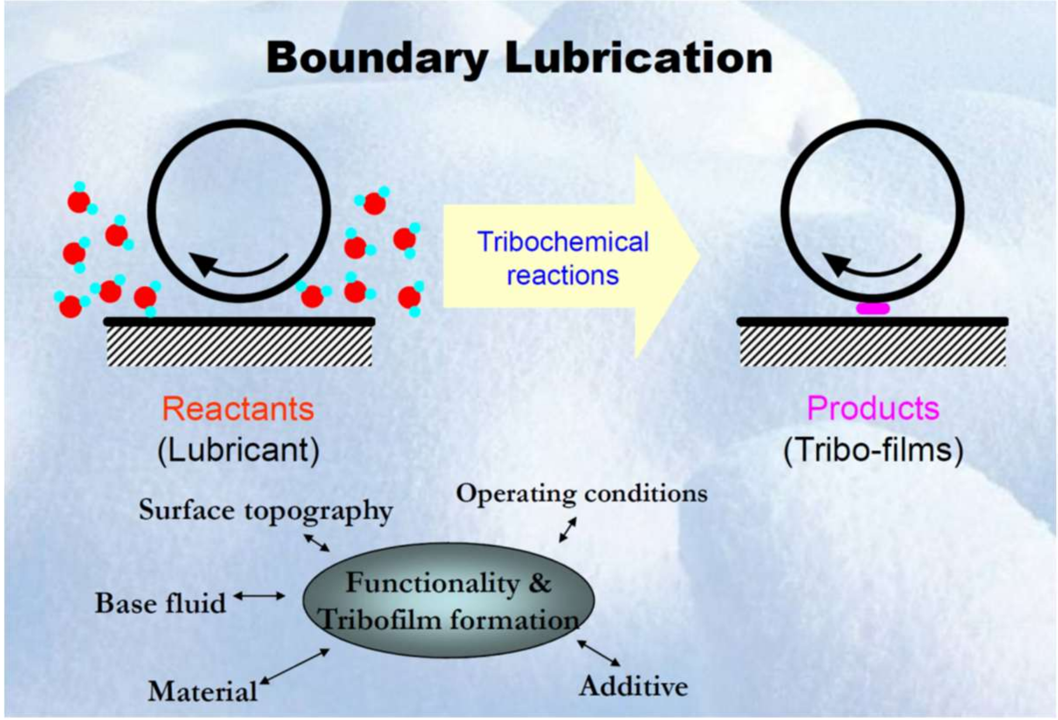
Compressive effects

Crack propagation

Sub-surface stress

Extreme pressures

Hydrodynamic action



Boundary Lubrication

Tribochemical reactions

Reactants
(Lubricant)

Products
(Tribo-films)

Surface topography

Operating conditions

Base fluid

Functionality &
Tribofilm formation

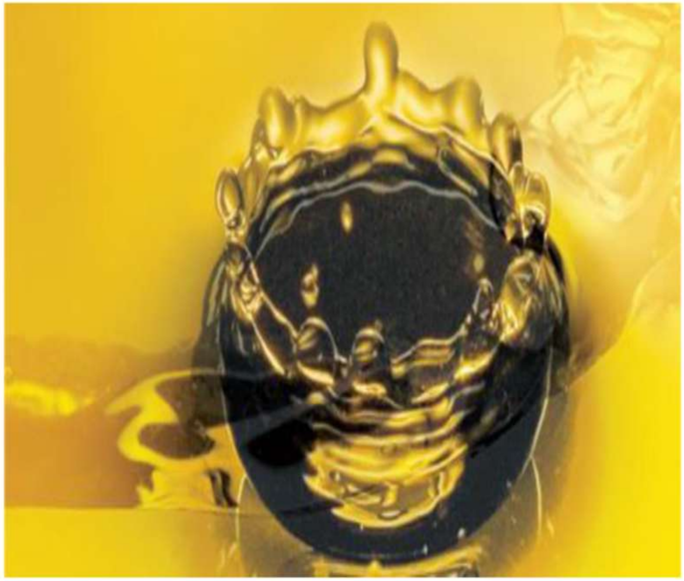
Material

Additive

The selection of a lubricant depends on various factors, including:

- The type of motion (linear, rotary, etc.)
- The load on the surfaces
- The operating temperature
- The environment (presence of contaminants, moisture, etc.)
- The desired performance characteristics (low friction, high load-carrying capacity, corrosion resistance, etc.)

Viscosity



Lubricant Maintenance and Optimization

1

Regular Testing

Analyze lubricant samples to monitor condition and contamination levels.

2

Filtration

Implement proper filtration systems to remove contaminants and extend lubricant life.

3

Scheduled Changes

Replace lubricants at recommended intervals to maintain optimal performance.

4

Continuous Monitoring

Use sensors and analytics to track lubricant performance in real-time.

Introduction

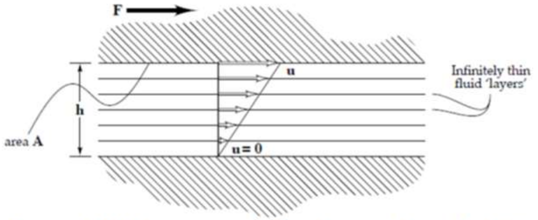
- Viscosity is a quantitative measure of a fluid's resistance to flow.

Dynamic (or Absolute) Viscosity:

- The dynamic viscosity(η) of a fluid is a measure of the resistance it offers to relative shearing motion.

$$\eta = F/\left[A \times (u/h)\right]$$

$$\eta = \tau/(u/h) \quad \text{N-s/m}^2$$



Kinematic Viscosity :

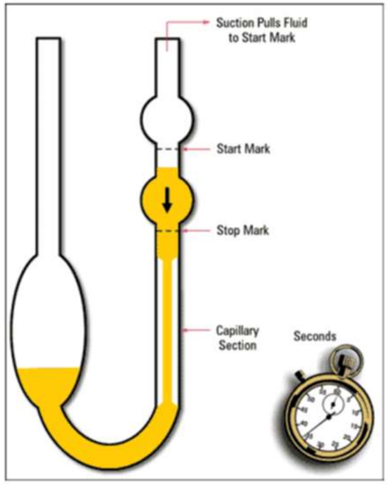
- It is defined as the ratio of absolute viscosity to the density of fluid.

$$\nu = \eta/\rho \qquad \text{m}^2/\text{s} \qquad ; \ \rho = \text{density of fluid}$$

Viscosity Measurements

Capillary Viscometers

- It gives the '**kinematic viscosity'** of the fluid. It is based on Poiseuille's law for steady viscous flow in a pipe.



$$\upsilon = \pi r^4 glt \; / \; 8LV = k(t_2 - t_1)$$

where:

υ	is the kinematic viscosity $[m^2/s]$;
r	is the capillary radius [m];
l	is the mean hydrostatic head [m];
g	is the earth acceleration $[m/s^2]$;
L	is the capillary length [m];
V	is the flow volume of the fluid $[m^3]$;
t	is the flow time through the capillary, $\mathbf{t} = (\mathbf{t}_2 - \mathbf{t}_1)$, [s];
k	is the capillary constant which has to be determined experimentally by applying a reference fluid with known viscosity, e.g. by applying freshly distilled water. The capillary constant is usually given by the manufacturer of the viscometer.

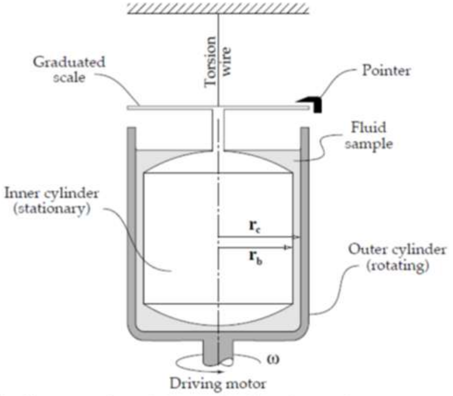
Viscosity Measurements

Rotational Viscometers

- These viscometer give the value of the ‘**dynamic viscosity’.**
- It is based on the principle that the fluid whose viscosity is being measured is sheared between two surfaces.
- In these viscometers one of the surfaces is stationary and the other is rotated by an external drive and the fluid fills the space in between.
- The measurements are conducted by applying either a constant torque and measuring the changes in the speed of rotation or applying a constant speed and measuring the changes in the torque.
- There are two main types of these viscometers: rotating cylinder and cone-on-plate viscometers

Viscosity Measurements

Rotating cylinder viscometer



Schematic diagram of a rotating cylinder viscometer.

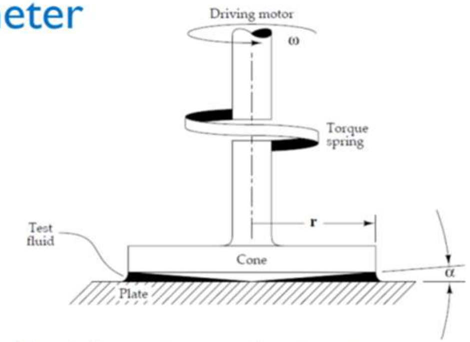
$$\eta = M(1/r_b^2 - 1/r_c^2) / 4\pi d\omega = kM / \omega$$

where:

η	is the dynamic viscosity [Pas];
r_b, r_c	are the radii of the inner and outer cylinders respectively [m];
M	is the shear torque on the inner cylinder [Nm];
ω	is the angular velocity [rad/s];
d	is the immersion depth of the inner cylinder [m];
k	is the viscometer constant, supplied usually by the manufacturer for each pair of cylinders [m^{-3}].

Viscosity Measurements

Cone-on-plate viscometer



Schematic diagram of a cone on plate viscometer.

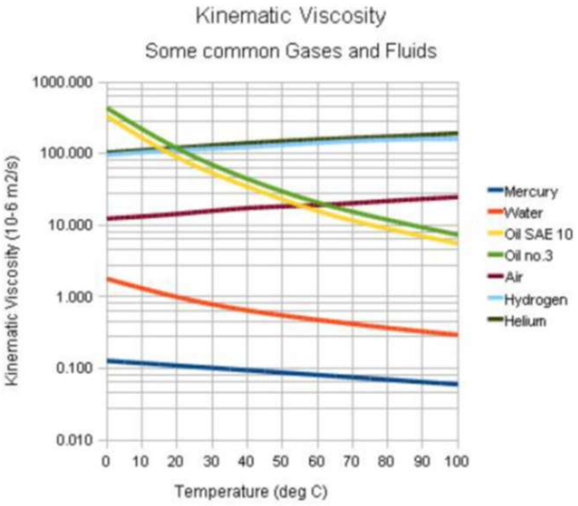
$$\eta = 3M\alpha\cos^2\alpha(1 - \alpha^2/2)\ /\ 2\pi\omega r^3 = kM\ /\ \omega$$

where:

η	is the dynamic viscosity [Pas];
r	is the radius of the cone [m];
M	is the shear torque on the cone [Nm];
ω	is the angular velocity [rad/s];
α	is the cone angle [rad];
k	is the viscometer constant, usually supplied by the manufacturer [m^{-3}].

Effects of temperature

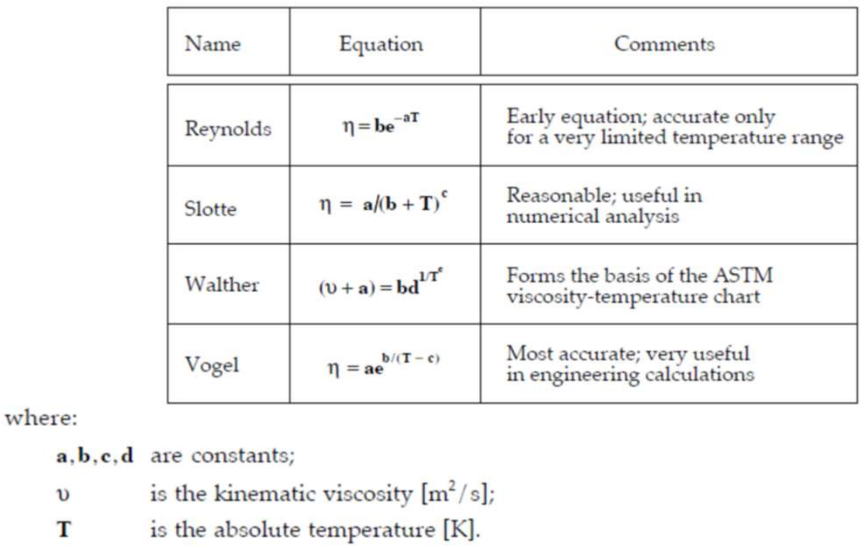
- The viscosity of liquids decreases with increase the temperature.
- The viscosity of gases increases with the increase the temperature.



Effects of temperature

- The lubricant oil viscosity at a specific temperature can be either calculated from the viscosity - temperature equation or obtained from the viscosity-temperature ASTM chart.

Viscosity-Temperature Equations



Name	Equation	Comments
Reynolds	$\eta = \mathbf{b}\mathbf{e}^{-\mathbf{aT}}$	Early equation; accurate only for a very limited temperature range
Slotte	$\eta = \mathbf{a}/(\mathbf{b} + \mathbf{T})^{\mathbf{c}}$	Reasonable; useful in numerical analysis
Walther	$(\upsilon + \mathbf{a}) = \mathbf{b}\mathbf{d}^{1/\mathbf{T}^{\mathbf{c}}}$	Forms the basis of the ASTM viscosity-temperature chart
Vogel	$\eta = \mathbf{a}\mathbf{e}^{\mathbf{b}/(\mathbf{T} - \mathbf{c})}$	Most accurate; very useful in engineering calculations

where:

$\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$ are constants;

υ is the kinematic viscosity $[\mathrm{m}^2/\mathrm{s}]$;

$\mathbf{T}$ is the absolute temperature [K].

Effects of temperature

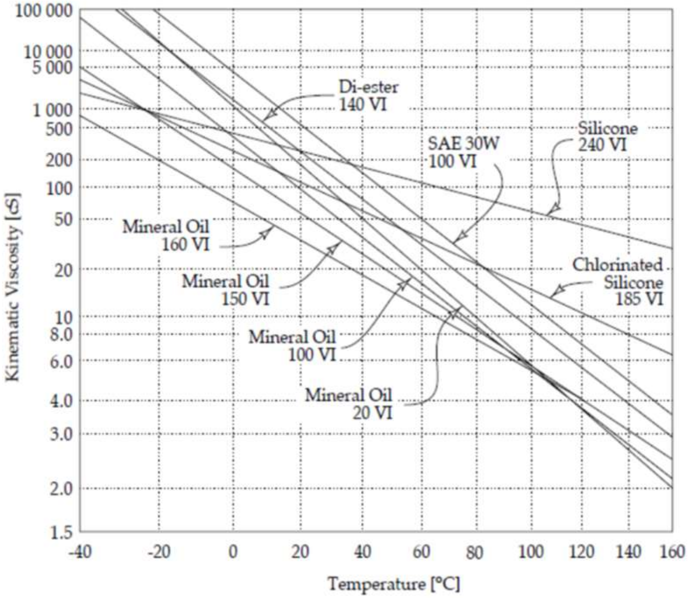


fig: Viscosity-temperature characteristics of selected oils

Viscosity index

- An entirely empirical parameter which would accurately describe the viscosity- temperature characteristics of the oils.
- The viscosity index is calculated by the following formula:

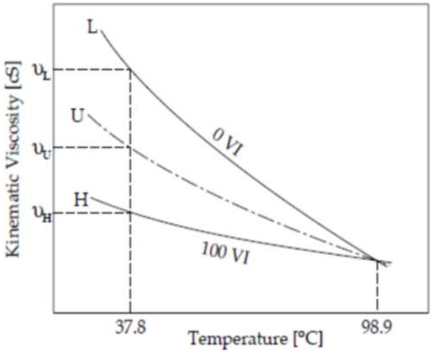
$$VI = (L - U)/ (L - H) * 10$$

where ,

VI is viscosity index

U is the kinematic viscosity of oil of interest

L and H are the kinematic viscosity of the reference oils



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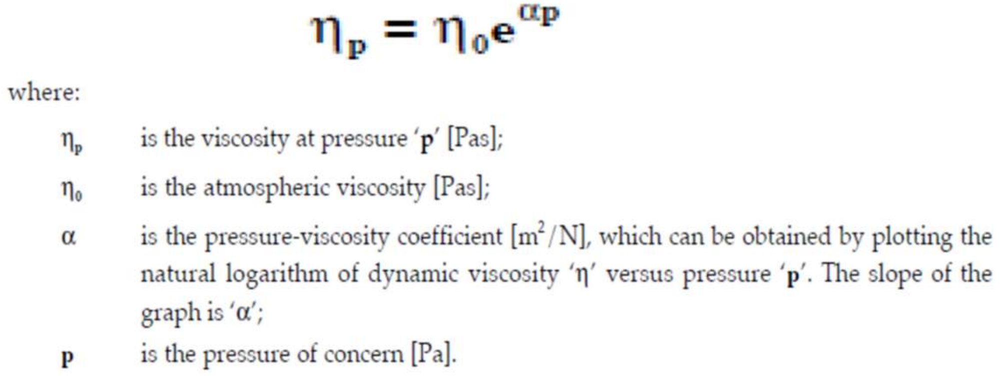
Effects of pressure

- Lubricants viscosity increases with pressure.
- For most lubricants this effect is considerably largest than the other effects when the pressure is significantly above atmospheric.
- The Barus equation :

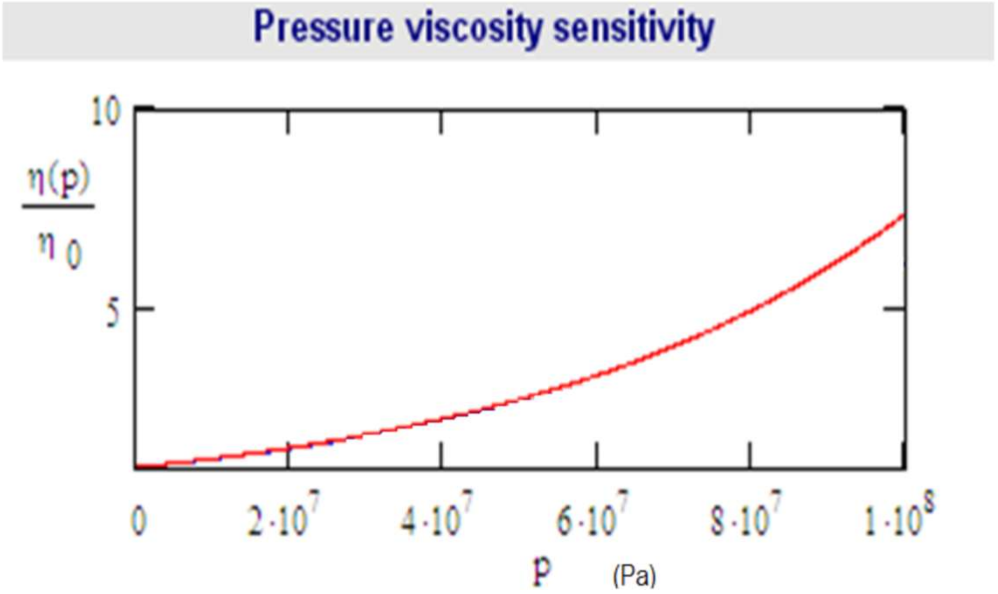


$$\eta_p = \eta_0 e^{\alpha p}$$

where:

η_p	is the viscosity at pressure '**p**' [Pas];
η_0	is the atmospheric viscosity [Pas];
α	is the pressure-viscosity coefficient [m^2/N], which can be obtained by plotting the natural logarithm of dynamic viscosity 'η' versus pressure '**p**'. The slope of the graph is 'α';
p	is the pressure of concern [Pa].

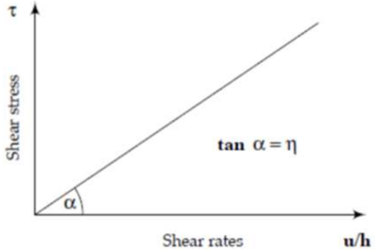
Effects of pressure



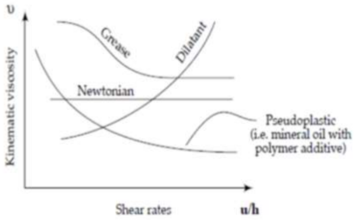
Viscosity - shear relationship

- For Newtonian fluids, shear stress linearly vary with the shear rate as shown in Figure. Viscosity is constant for this kind of fluid.

$$\tau = \eta \left(u/h \right)$$



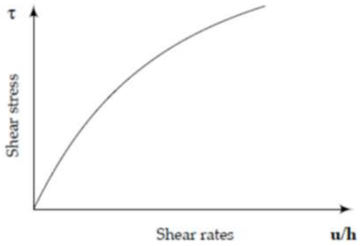
- Non Newtonian fluid doesn't follow the linear relation between viscosity and shear rate.

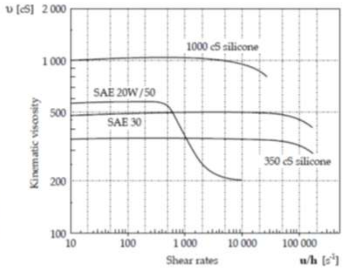


Viscosity – shear relationship

Pseudoplastic Behaviour

- Pseudoplastic or shear thinning and is associated with the thinning of the fluid as the shear rate increases.





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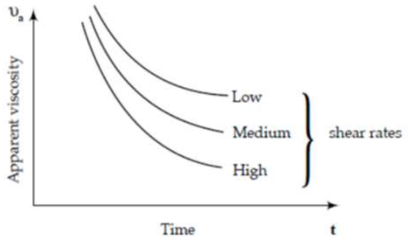
- The opposite of this behavior is known as inverse thixotropic.



Applications

- Selection of lubricants for various purpose.
  - we can choose an optimum range of viscosity for engine oil.
  - for high load and also for speed operation high viscous lubricants is required.
- In pumping operation
  - for high viscous fluid high power will require.
  - for low viscous fluid low power will require.
- In making of blend fuel
  - less viscous fuels easy to mix.
- In the operation of coating and printing.

Future challenges in tribology

- Light weight machines/high power densities
- Lubricants for extreme operating temperature (low and high temp.)
- Environmental protection
- Predictability
- Controllability
- Profitability
- Sustainability